INDIANA UNIVERSITY
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Collaboration

# Consistency of perfect fluidity and high pT parton propagation in semi-quark-gluon-monopole plasmas

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11th International Workshop on High-pT Physics in the RHIC & LHC Era
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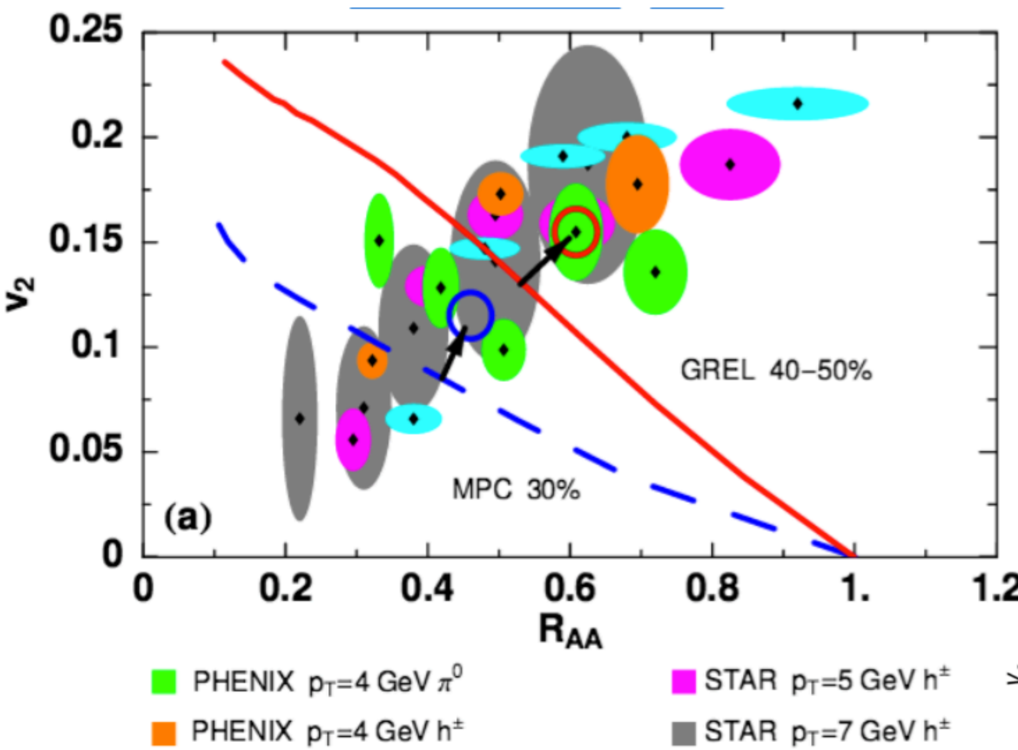
# Outline

- A hard lesson from data of leading hadrons' $R_{AA}$ and $v_2$ for pQCD energy loss models
- Nonperturbative ingredients of sQGP near $T_c$
- CUJET3.0 = pQCD/(D)GLV + semi-Quark-Gluon-Monopole Plasmas
- Jet quenching parameter and perfect fluidity
- Summary and outlook

# Leading hadrons: $v_2$ and $R_{AA}$ correlation

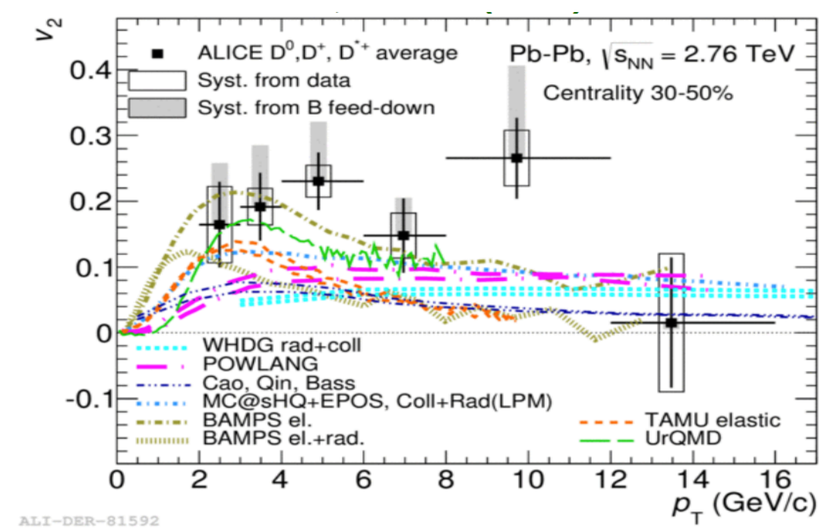



MPC- D.Molnar
Parton Cascade
Varied σ(gg)

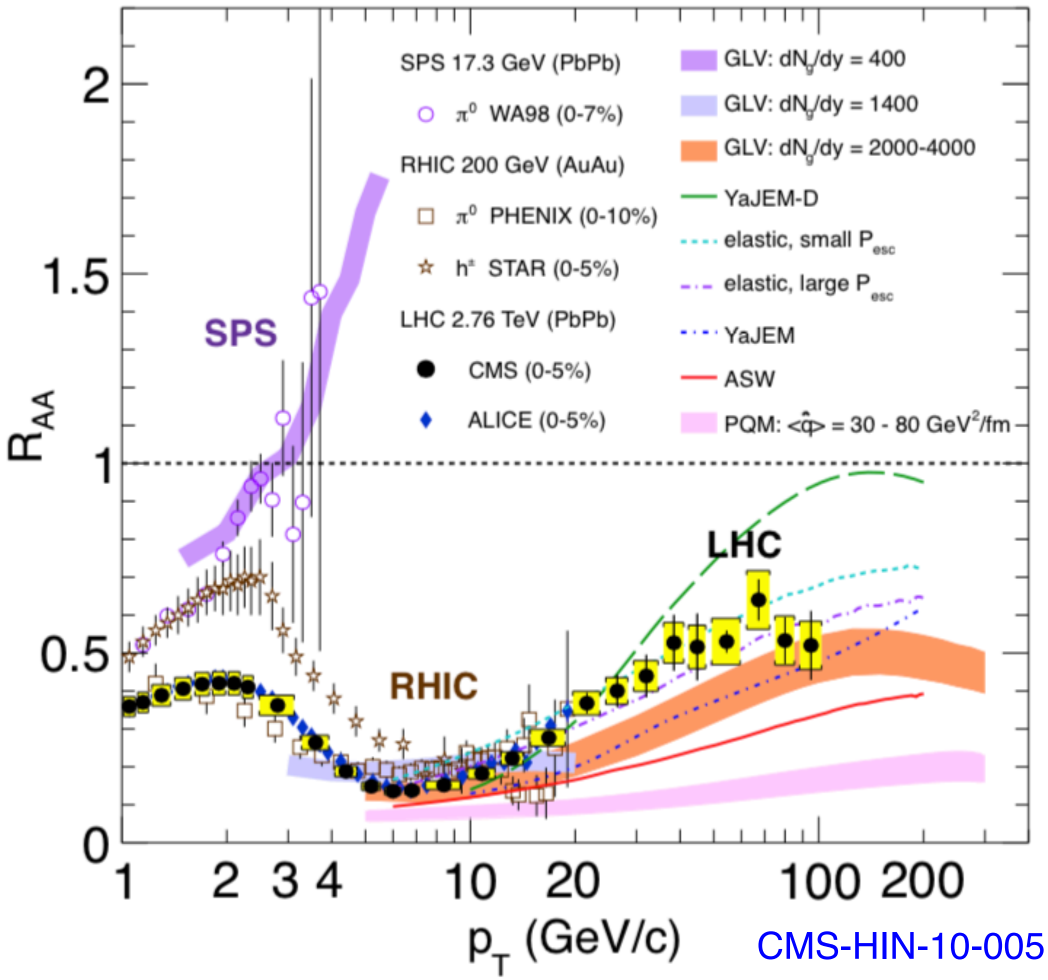
GREL-W.Horowitz
Geometric Radiative
Energy Loss
Varied $\alpha_s$

Horowitz, nucl-th/0511052

- Interesting physics hides in the high pT v2 of light hadrons/open heavy flavors



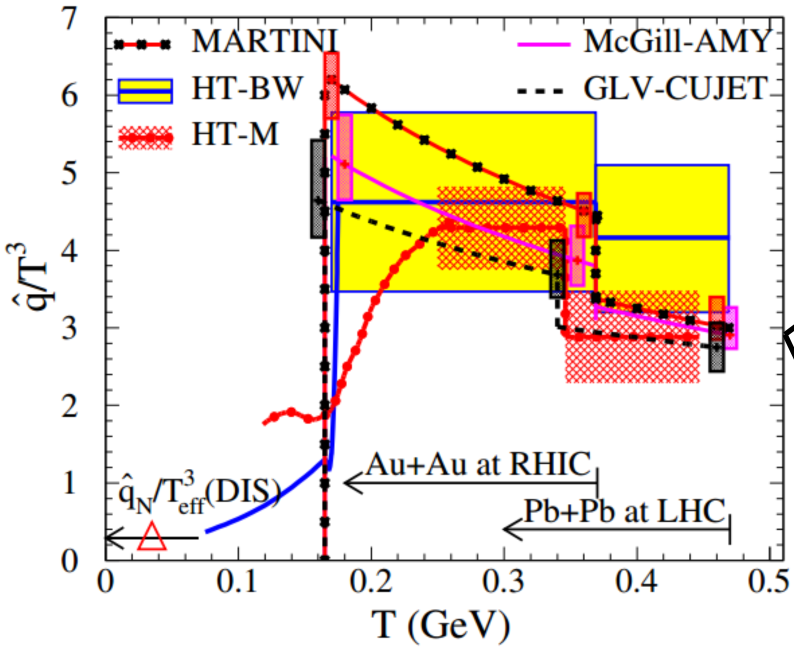
# Leading hadrons: quantitative lessons from simultaneously describing RHIC and LHC data




CMS-HIN-10-005

- Jet opacity scales weaker than linearly with medium density → running coupling, but how large?
- Even for leading hadrons a quantitative description of [RAA & v2] + [RHIC & LHC] is non-trivial

# From $R_{AA}$ constrained jet quenching parameter to $v_2$ and $\eta/s$

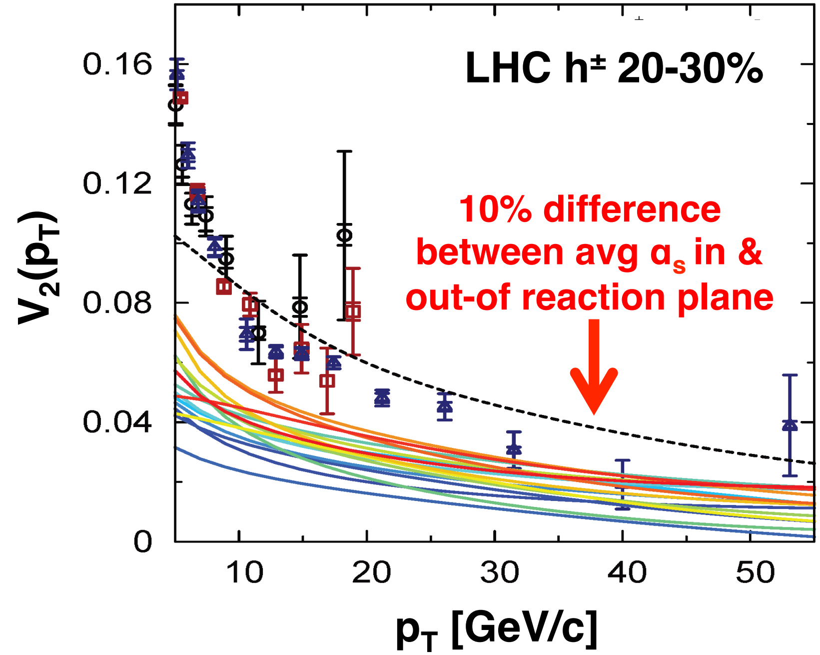



JET Collaboration, PRC 90, 014909 (2014)

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

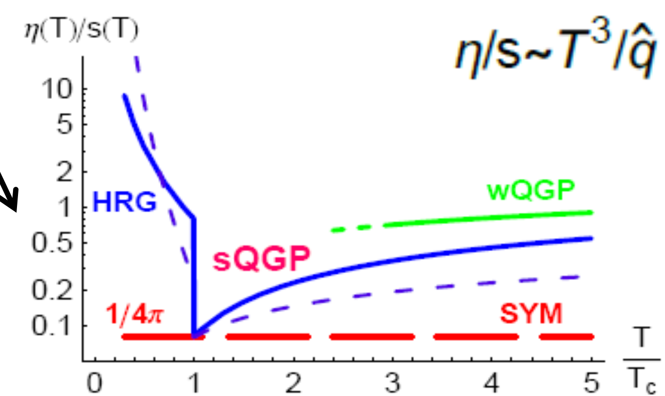
$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \ \text{at} \ \ \begin{matrix} T = 370\ \mathrm{MeV}, \\ T = 470\ \mathrm{MeV}, \end{matrix}$$

- 50% underestimation of high $p_T$ $v_2$



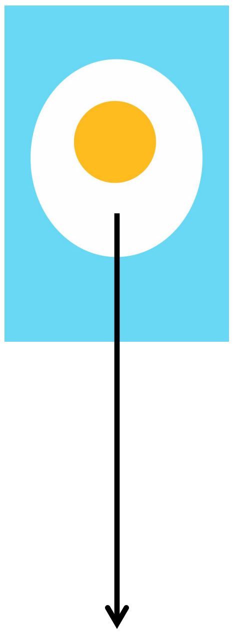

JX, Buzzatti, Gyulassy, JHEP 2014

- Inconsistency between perfect fluidity and pQCD jet quenching




Hirano, Gyulassy, NPA 2006

# The Liao-Shuryak bump solution to the high-$p_T$ $v_2$ puzzle



Egg white dominates the observed egg anisotropy

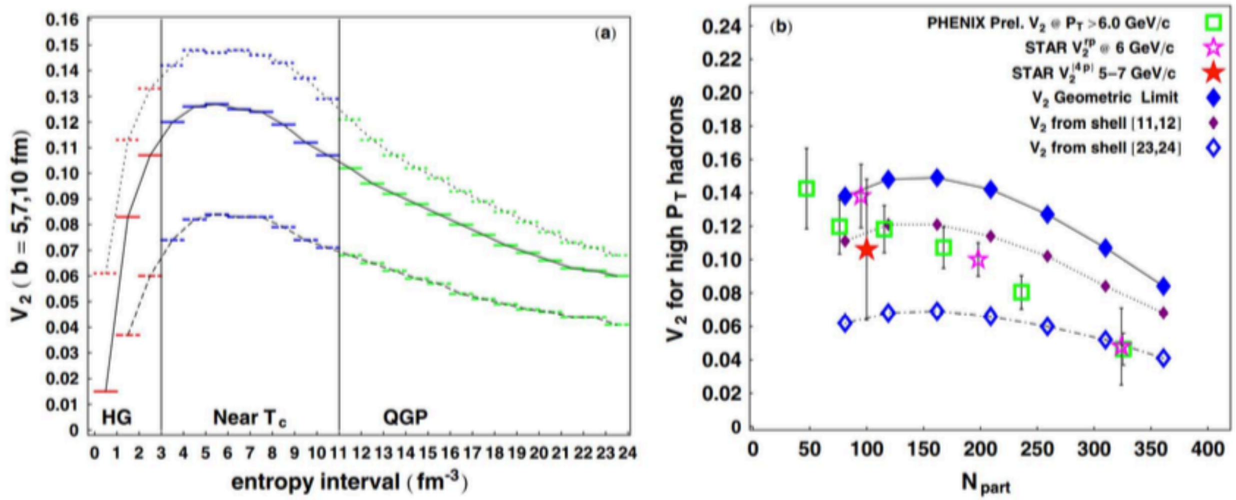
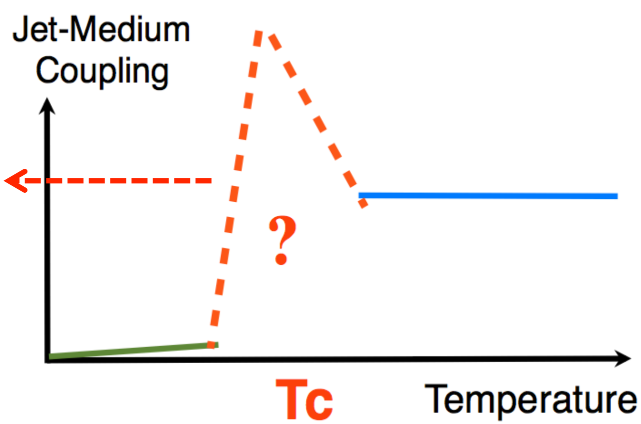
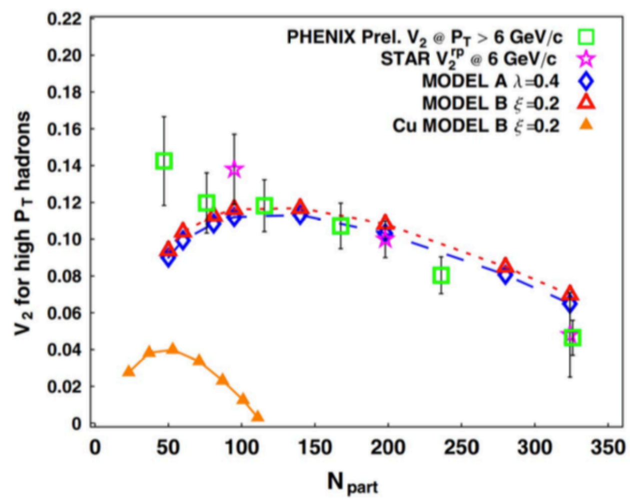



**Figure 3.17:** *Left: The v2 obtained for each entropy shell at different centralities. Right: $v_2^{\max}$ for high $p_T$ hadrons calculated at different $N_{\text{part}}$ compared with available RHIC data.*



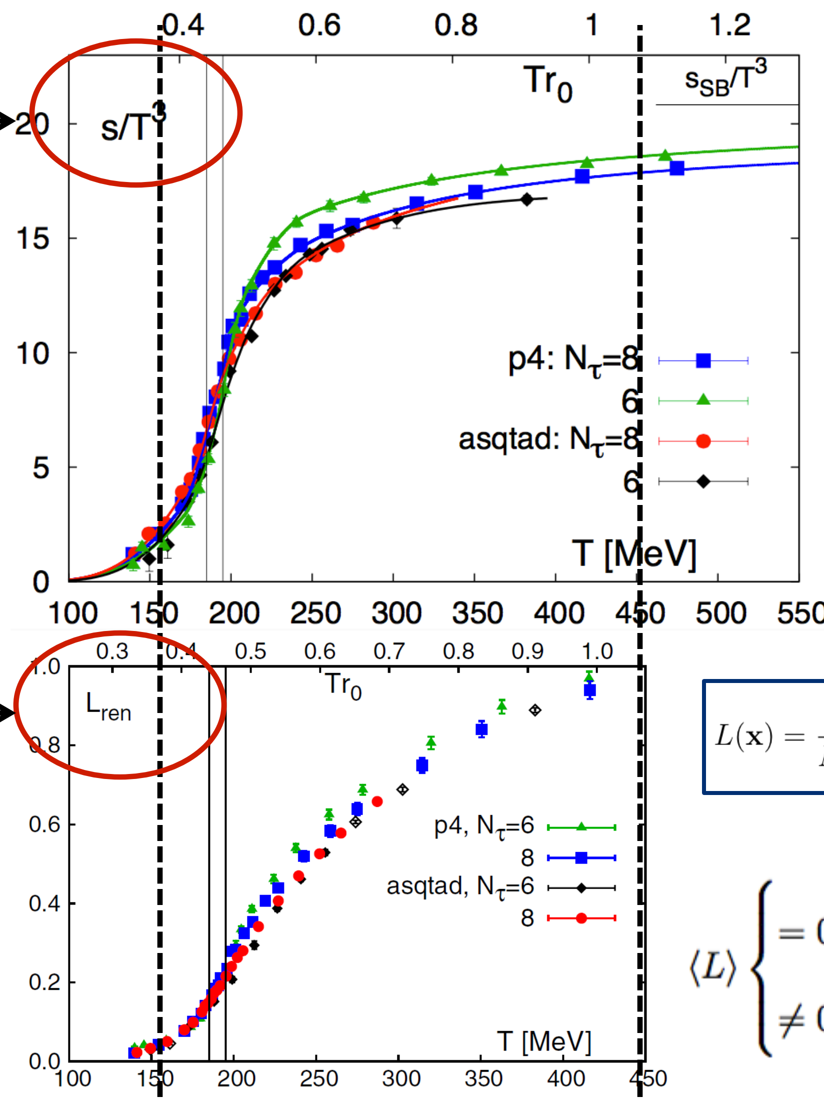

Liao & Shuryak, PRL 2009

- Origin of the near Tc enhancement? Is it consistent with lattice data and perfect fluidity?

# The nonperturbative medium near $T_c$ from lattice

**Thermal**

**Chromo**




Bazavov et al, PRD 2009

$$L(\mathbf{x}) = \frac{1}{N_c}\mathrm{tr}\mathcal{P}\exp\left[ig\int_0^{1/T} A_4(\tau,\mathbf{x})d\tau\right]$$

$$\langle L\rangle \propto e^{-F_Q/T}$$

$$\langle L\rangle \begin{cases} = 0, & \text{confined } (T < T_c) \\ \neq 0, & \text{deconfined } (T > T_c) \end{cases}$$

❖ What can be pumped out of vacuum to account for the “missing” degrees of freedom?

# Color confinement: Dual Superconductivity

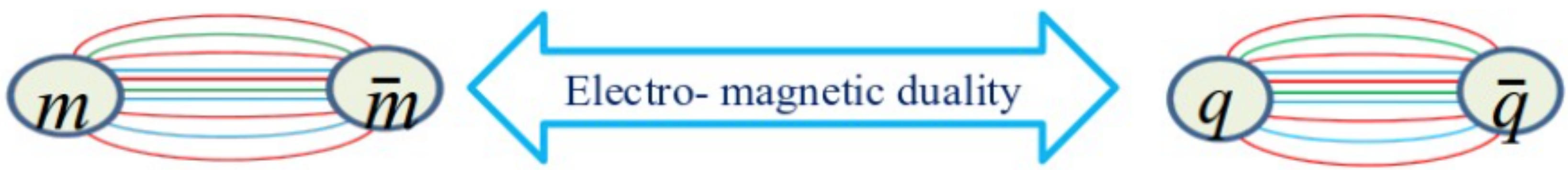
- Dual superconductivity is a promising mechanism for quark confinement. [Y.Nambu (1974). G.'t Hooft, (1975). S.Mandelstam, (1976) A.M. Polyakov (1975)]

**superconductor**

- Condensation of electric charges (Cooper pairs)
- Meissner effect: Abrikosov string (magnetic flux tube) connecting monopole and anti-monopole
- Linear potential between monopoles

**dual superconductor**

- Condensation of magnetic monopoles
- Dual Meissner effect: formation of a hadron string (chromo-electric flux tube) connecting quark and antiquark
- Linear potential between quarks

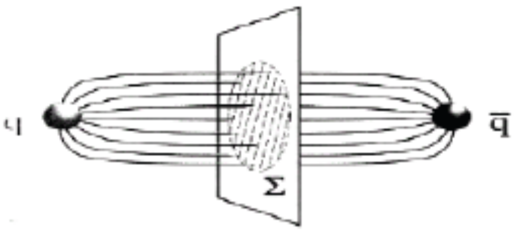



Slide of Akihiro & Shibata @ Trento 2013

# The magnetic scenario of sQGP

T<< Lambda_QCD | T ~ Lambda_QCD | T>> Lambda_QCD

***Vacuum: confined*** — **Tc** — sQGP — ***wQGP: screening*** — **T**

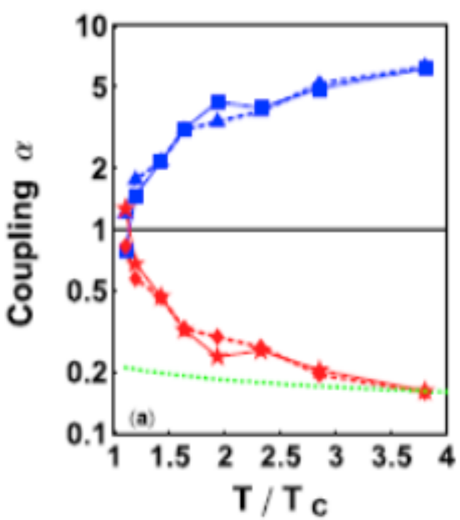


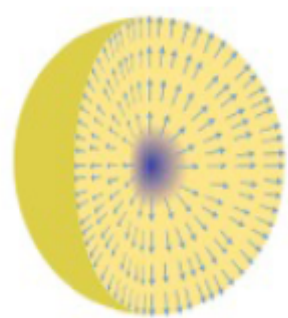

**Emergent plasma with <u>E & M</u> charges:**
chromo-magnetic monopoles are the "missing DoF"

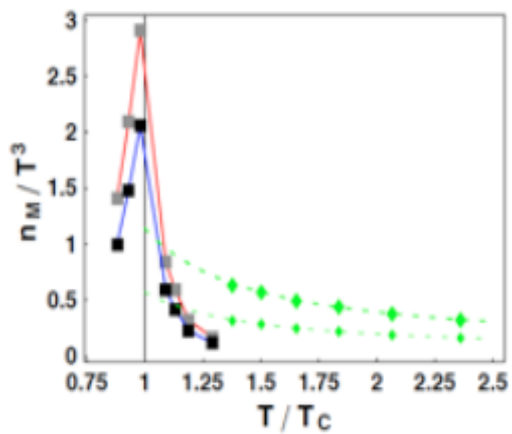
***Plasma of E-charges***
***E-screening: g T***
***M-screening: g^2 T***

***Electric Flux Tube:***
***Magnetic Condensate***

$$\alpha_E * \alpha_M = 1.$$






*Phys.Rev.C75:054907,2007; Phys.Rev.Lett.101:162302,2008; Phys.Rev.C77:064905,2008; Phys.Rev.D82:094007,2010; Phys.Rev.Lett.109:152001,2012.*

❖ Slide courtesy of Jinfeng Liao

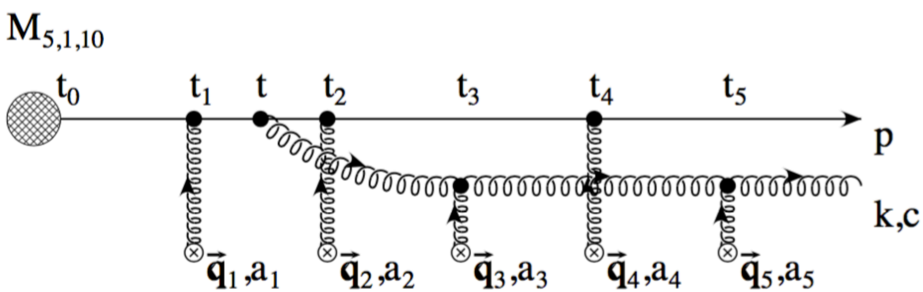
# How to include monopoles in the (D)GLV energy loss formalism?

$$x\frac{dN_g^n}{dx\,d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\frac{1}{n!}\left(\frac{L}{\lambda_g}\right)^n \int \prod_{i=1}^{n}\left(d^2\mathbf{q}_i\left(|\bar{v}_i(\mathbf{q}_i)|^2-\delta^2(\mathbf{q}_i)\right)\right)$$

$$\times\; -2\,\mathbf{C}_{(1\cdots n)}\cdot\sum_{m=1}^{n}\mathbf{B}_{(m+1\cdots n)(m\cdots n)}$$

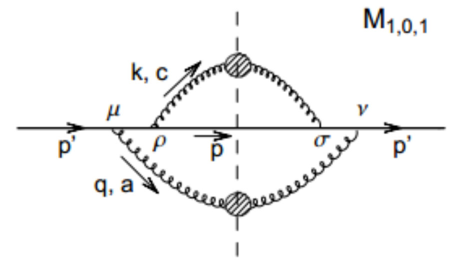
$$\times\left(\cos\left(\sum_{k=2}^{m}\Omega_{(k\cdots n)}\Delta z_k\right)-\cos\left(\sum_{k=1}^{m}\Omega_{(k\cdots n)}\Delta z_k\right)\right)$$

Gyulassy, Levai, Vitev, 2000; Djordjevic & Gyulassy, 2004




$$|\bar{v}_i(\mathbf{q}_i)|^2 = \frac{\mu_i{}^2}{\pi(\mathbf{q}_i^2+\mu_i{}^2)^2}$$

Gyulassy and Wang, 1996




$$\lambda_{\rm dyn} \Longleftrightarrow \lambda_{\rm stat} = \frac{\lambda_{\rm dyn}}{c(n_f)}$$

$$\left[\frac{\mu^2}{\boldsymbol{q}^2(\boldsymbol{q}^2+\mu^2)}\right]_{\rm dyn} \Longleftrightarrow \left[\frac{\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}\right]_{\rm stat}$$

Djordjevic and Heinz, 2008

# CUJET3.0 = pQCD/DGLV + semi-QGP + monopoles

$$\frac{dE}{dx} \propto \ldots \int_{q^2} \frac{n_e\, \alpha_s^2(q^2)\, f_E^2}{q^2(q^2 + f_E^2 \mu^2)} \ldots$$

Original DGLV has only quark/gluon scattering centers

$$\frac{dE}{dx} \propto \ldots \int_{q^2} \left[ \frac{n_e \boxed{(\alpha_s(q^2)\alpha_s(q^2))}\, f_E^2}{q^2(q^2 + f_E^2 \mu^2)} + \frac{n_m \boxed{(\alpha_s^e(q^2)\alpha^m(q^2))}\, f_M^2}{q^2(q^2 + f_M^2 \mu^2)} \right] \ldots$$

Include both color-electric and -magnetic scattering centers

$$\frac{dE}{dx} \propto \ldots \int_{q^2} \frac{n_T}{(q^2 + f_E^2 \mu^2)(q^2 + f_M^2 \mu^2)} \times \kappa(q^2, T)$$

=1

$$\kappa(q^2, T) \equiv \boxed{\alpha_s^2(q^2)}\, \chi_T \left( f_E^2 + \frac{f_E^2 f_M^2 \mu^2}{q^2} \right) + (1 - \chi_T) \left( f_M^2 + \frac{f_E^2 f_M^2 \mu^2}{q^2} \right)$$

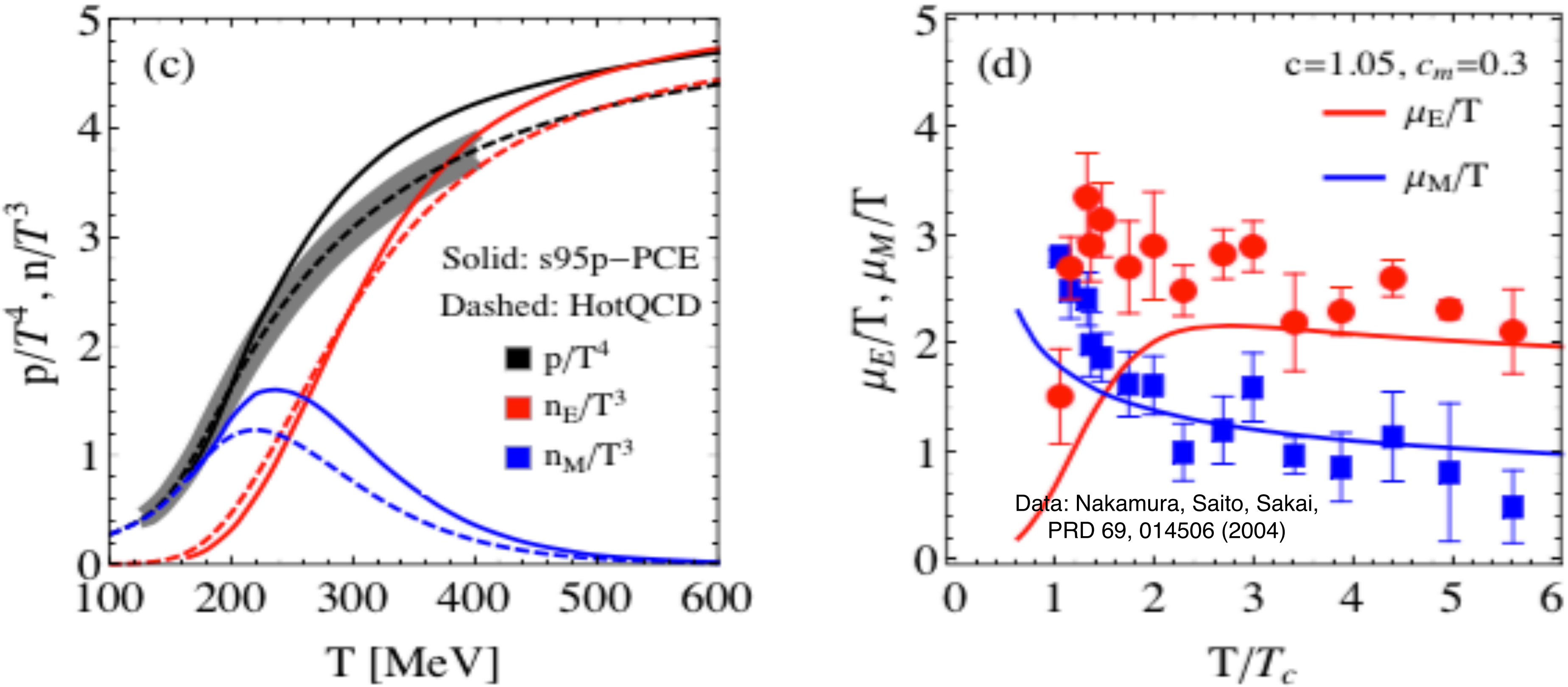
$$\chi_T = c_q L + c_g L^2$$

Semi-QGP (Pisarski, Hidaka et al.): Polyakov Loop suppressed color-electric components

The electric scales as a power law of the Polyakov loop as in the semi-QGP model, the left over “missing” DOFs are the mag. monopoles

$$\alpha_s(Q^2) = \frac{\alpha_c}{1 + \frac{9\alpha_c}{4\pi} \log\left(\frac{Q^2}{T_c^2}\right)}$$

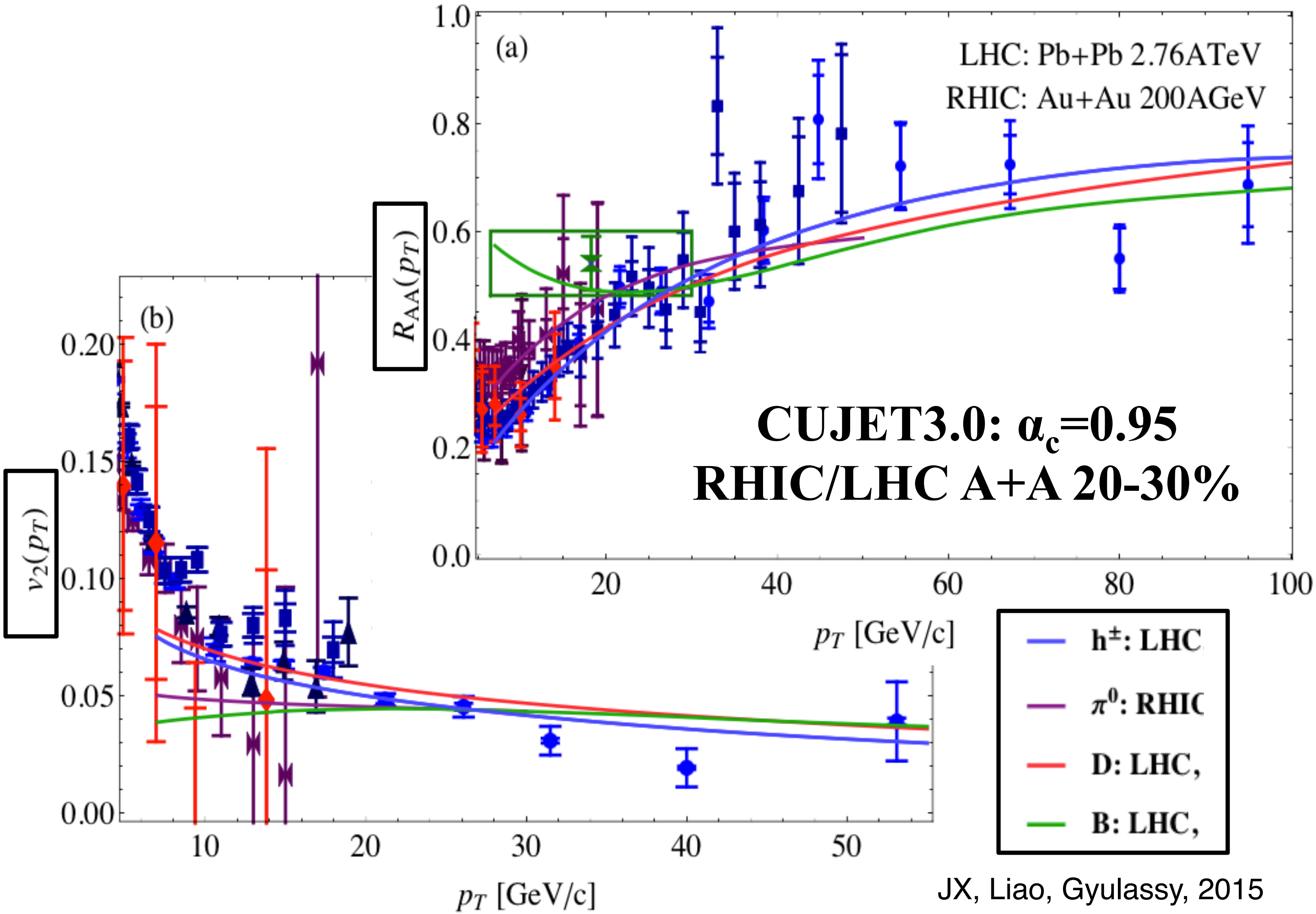
# Lattice Constraints: Polyakov Loop, EOS, E & M Screening Masses




JX, Liao, Gyulassy, 2015

- The CUJET3.0 implementation of the color-electric and color-magnetic components are well constrained by available lattice data of Polyakov loop, EOS and E & M screening masses
- Non-vanishing M screening across all temperatures, monopole dof's dominate $T=1\text{-}1.5T_c$

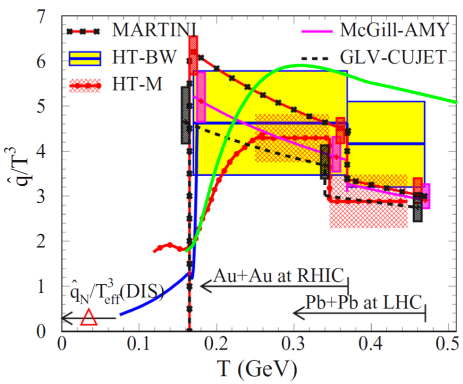
# CUJET3.0 [pQCD/DGLV + sQGMP] simultaneously describes high $p_T$ [$R_{AA}$ & $v_2$] + [light & heavy] + [RHIC & LHC]



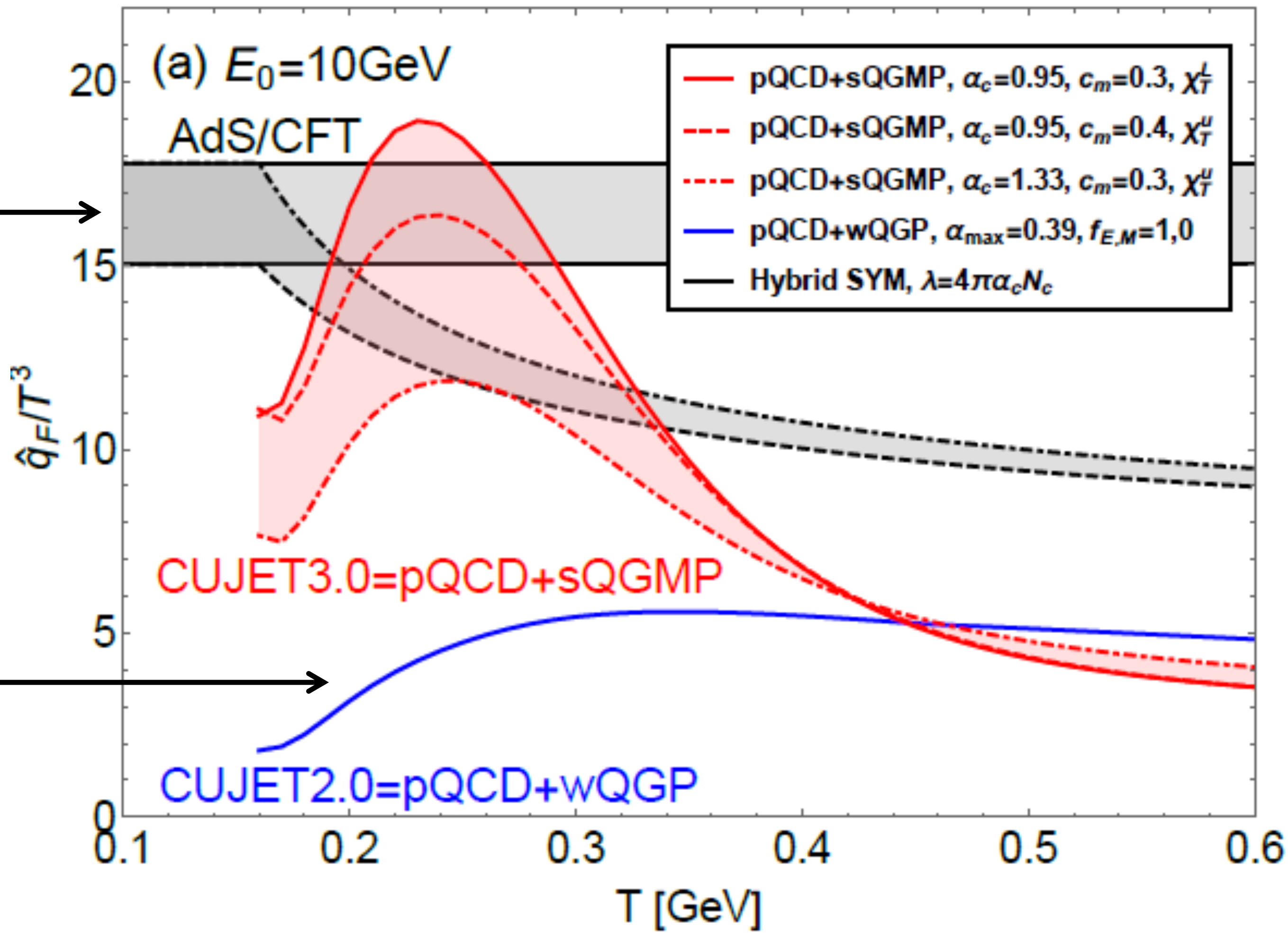

JX, Liao, Gyulassy, 2015

# CUJET3.0: qhat in sQGMP

Liu et al. PRL 2006
$\hat{q} \approx 26.69\sqrt{\lambda/4\pi}T^3$



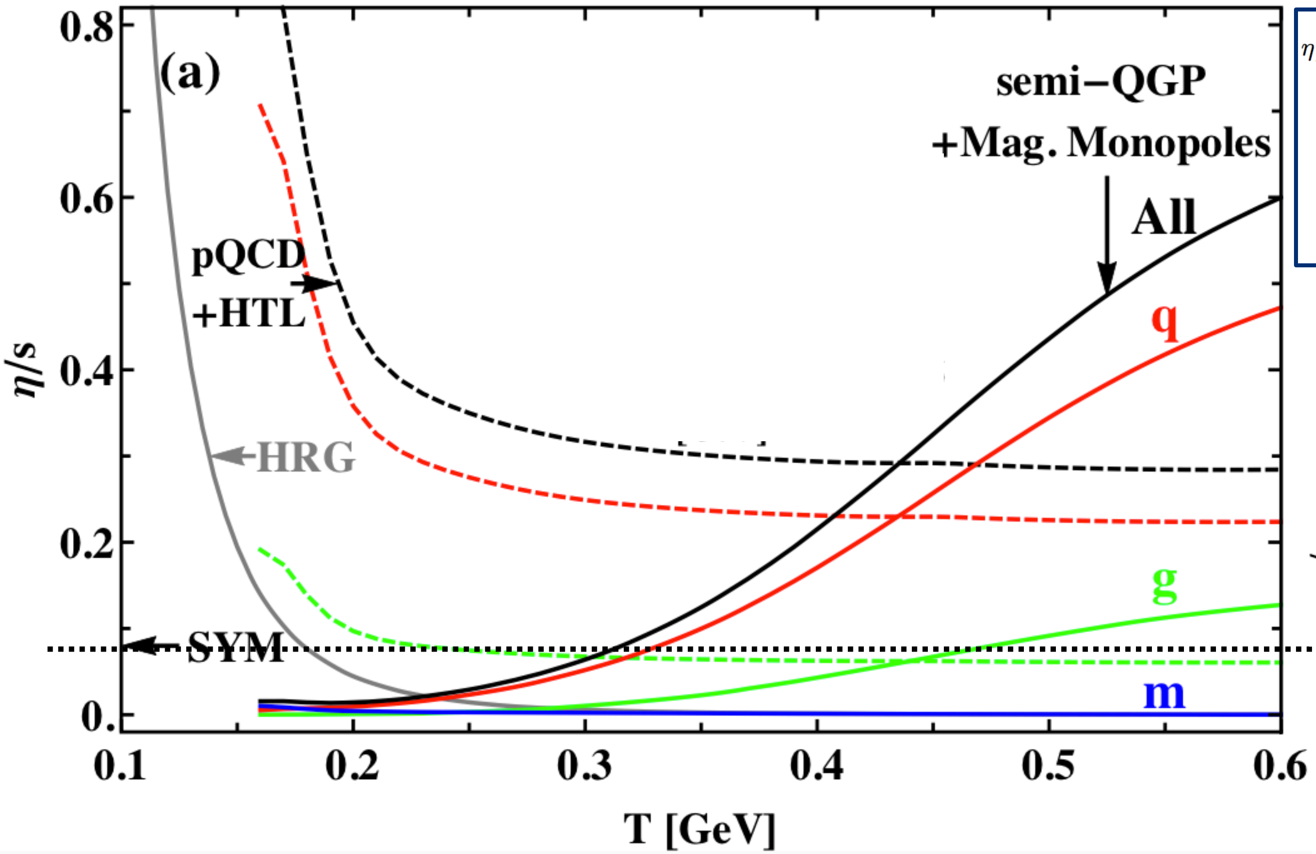

JET Collaboration, PRC 2014




JX, Liao, Gyulassy, CPL 2015, JHEP 2016

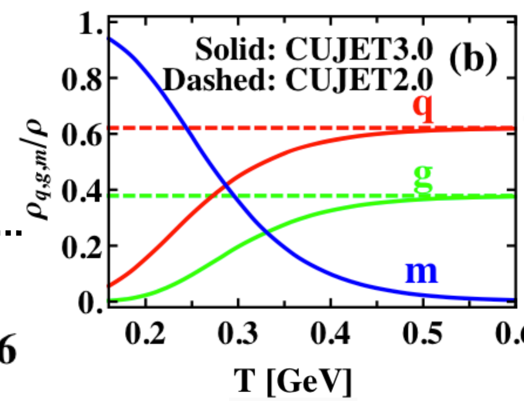
- ❖ The qhat/$T^3$ from CUJET3.0 shows a bump near $T_c$ whose magnitude is close to the strong coupling AdS limit, the bump peaked at T~1.5$T_c$
- ❖ At high T the small difference in v3.0 and v2.0 comes from different screening structures

# pQCD/DGLV + sQGMP: η/s(T)




$$
\begin{aligned}
\eta/s &= \frac{1}{s}\frac{4}{15}\sum_a \rho_a \langle p\rangle_a \lambda_a^{\perp} \\
&= \frac{4T}{5s}\sum_a \rho_a \left(\sum_b \rho_b \int_0^{\langle S_{ab}\rangle/2} dq_\perp^2 \frac{4q_\perp^2}{\langle S_{ab}\rangle}\frac{d\sigma_{ab}}{dq_\perp^2}\right)^{-1} \\
&= \frac{18T^3}{5s}\sum_a \rho_a/\hat{q}_a(T, E=3T) \ .
\end{aligned}
$$

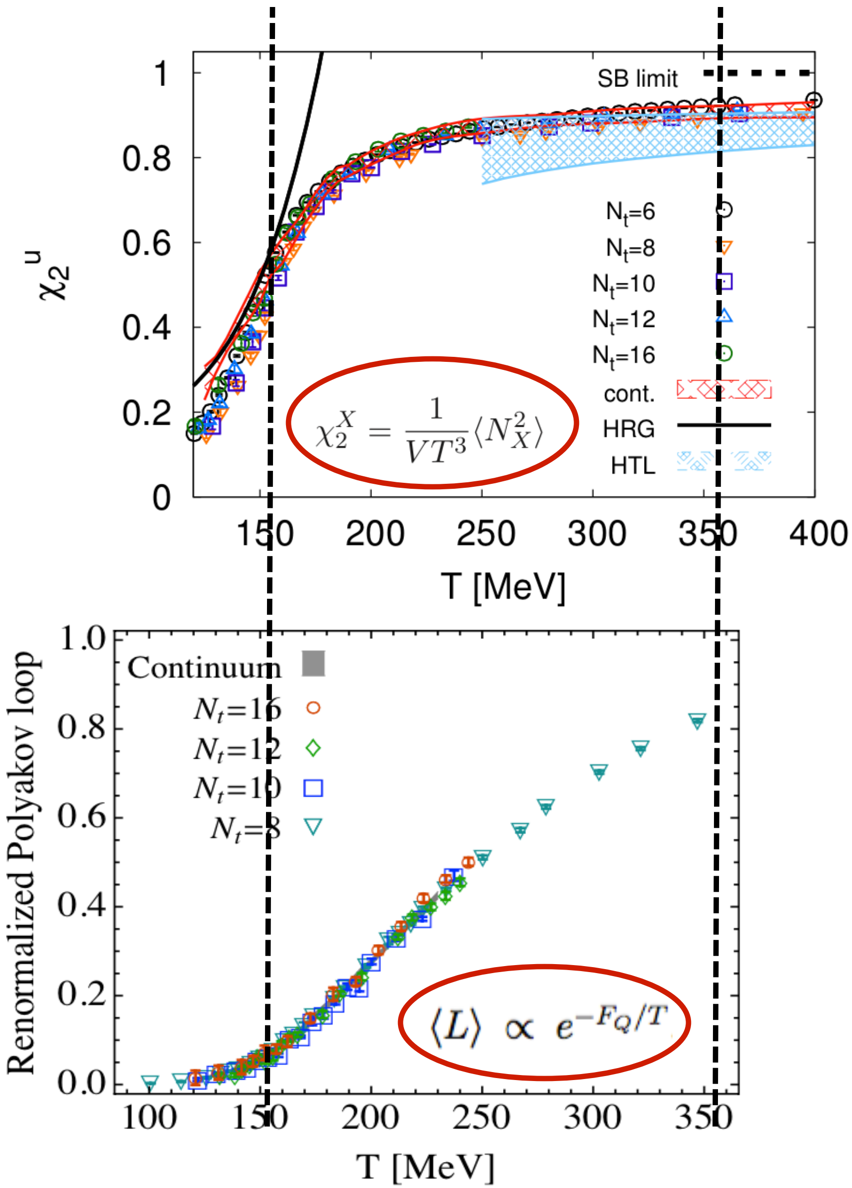
Danielewicz & Gyulassy, PRD 1985
Hirano & Gyulassy, NPA 2006
Majumder, Muller, Wang, PRL 2007



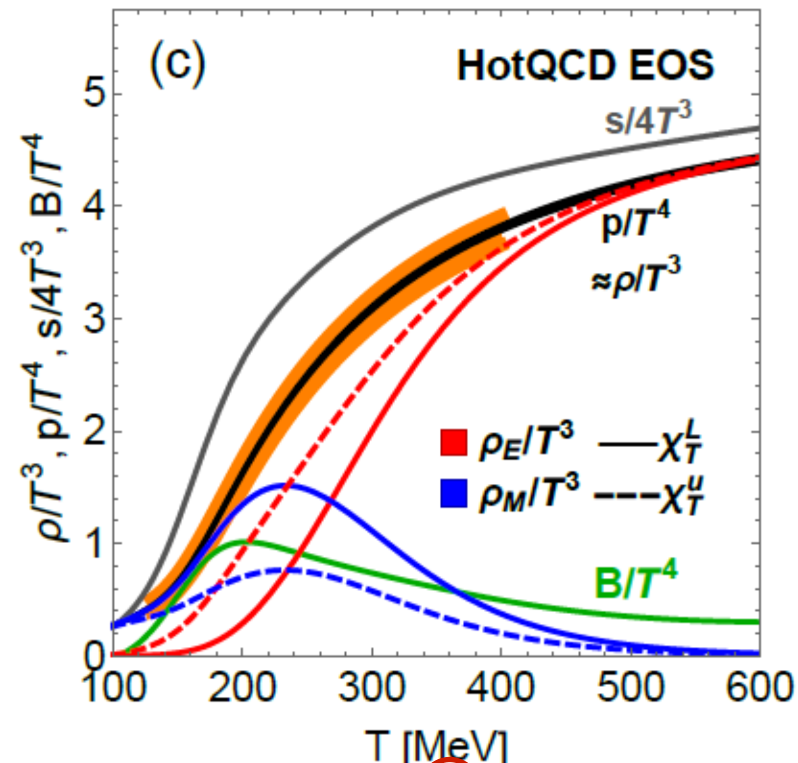

JX, Liao, Gyulassy, CPL 2015; HRG η/s from: Noronha-Hostler et al, PRL 2009, Niemi et al, PRL 2011

❖ CUJET3.0 provides a quantitative connection between the jet transport properties that control the hard jet quenching observables and the bulk viscous transport properties that control the soft "perfect fluidity" of QGP observed at RHIC and LHC.

# The subtlety of deconfinement: Quark number susceptibility vs Polyakov loop




Wuppertal-Budapest Collaboration, JHEP 2012



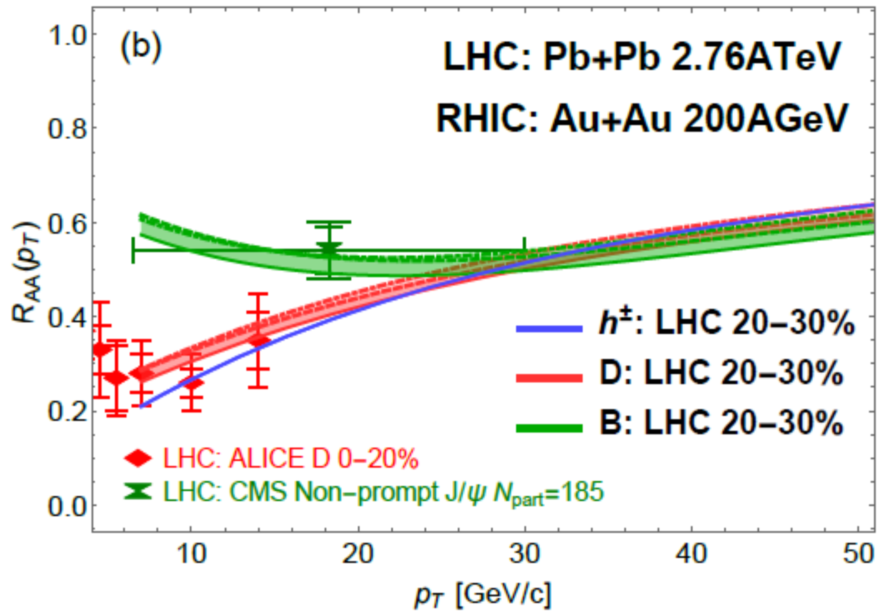

$$\chi_T^L(T) = c_q\, L(T) + c_g\, L^2(T)$$

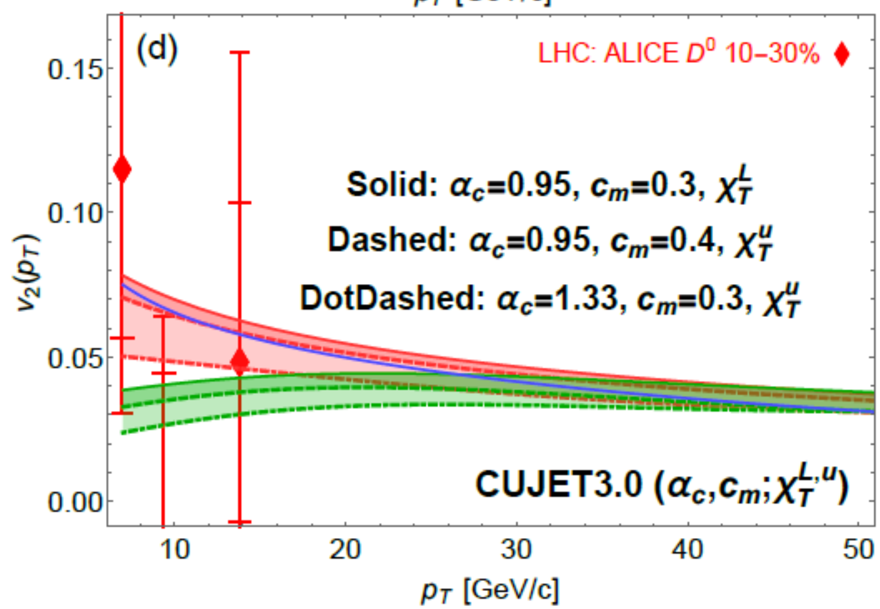
$$\chi_T^u = c_q\, \tilde{\chi}_2^u + c_g\, L^2$$

- ❖ Quark DOFs in the medium are light and dynamic than being heavy and static → using quark number susceptibility instead of Polyakov loop for the deconfinement rate of quarks near $T_c$
- ❖ High pT observables in CUJET3.0 can be sensitive to this near-$T_c$ thermodynamics

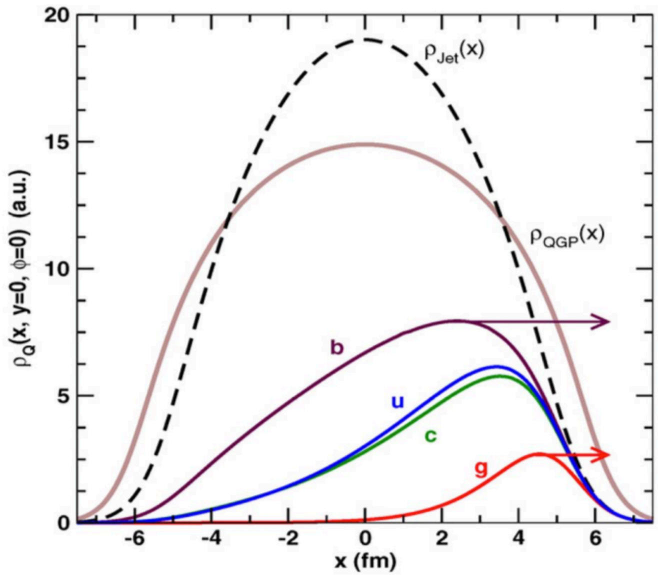
JX, Liao, Gyulassy, JHEP 2016

# CUJET3.0: connecting confinement physics and high pT observables



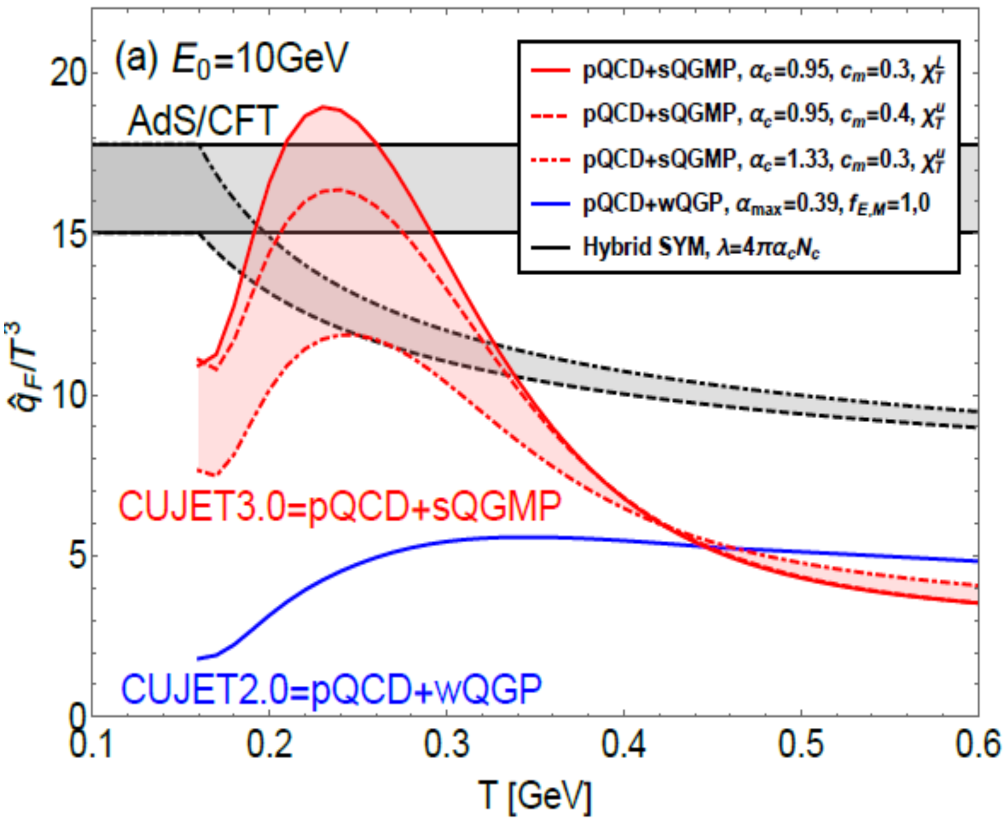

JX, Liao, Gyulassy, JHEP 2016

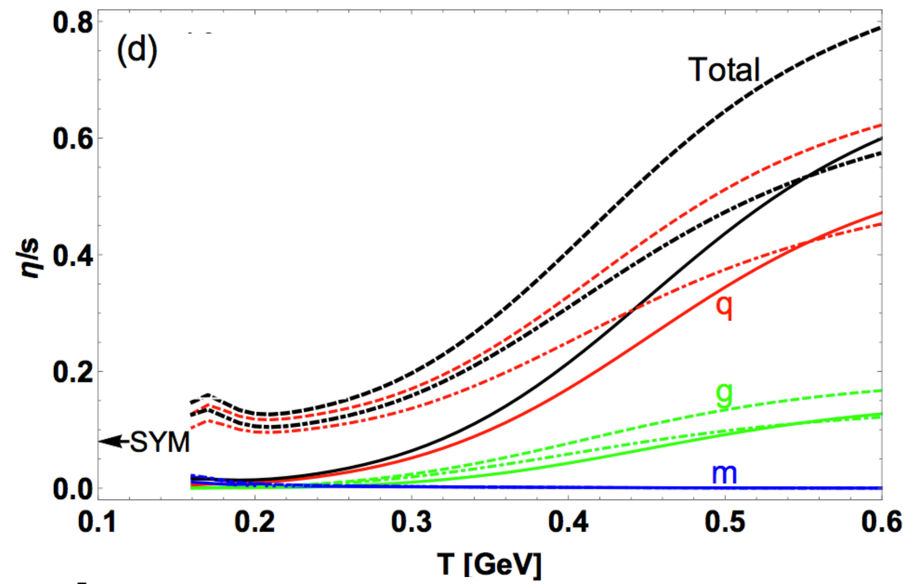


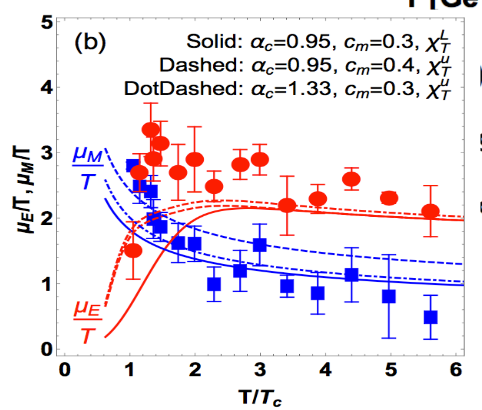

The x-coordinate distribution of surviving $p_T$ =15 GeV jets along +x direction, c.f. WHDG, NPA 2007

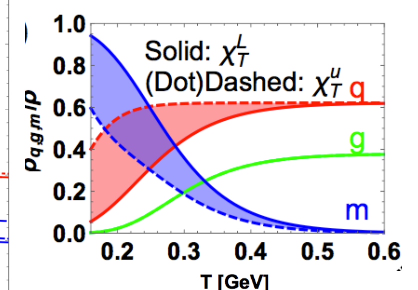
- Parameters are constrained using charged particle RAA at LHC
- The difference between open heavy flavor's $R_{AA}/v_2$ in CUJET3.0 with a "fast" and a "normal" deconfinement rate may be tested with data
- The ratio of D or B and charged particle's high $p_T$ $R_{AA}$ or $v_2$ may be a better observable to distinguish

# The qhat and shear viscosity with a “fast” deconfinement rate



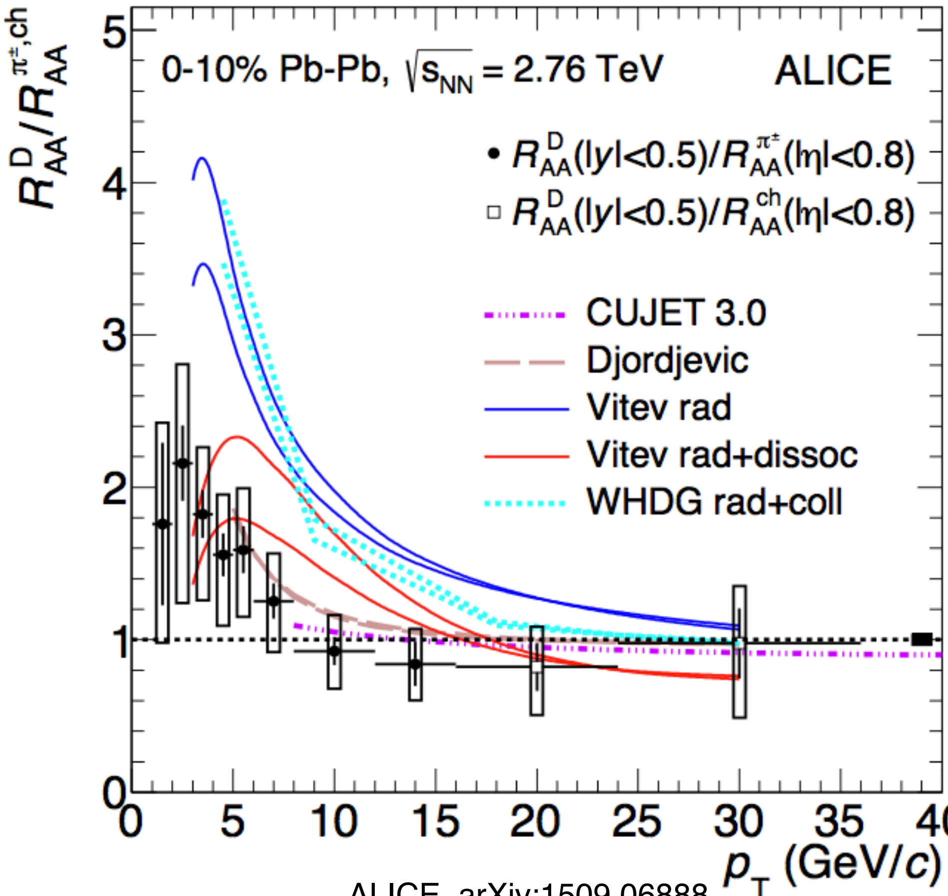



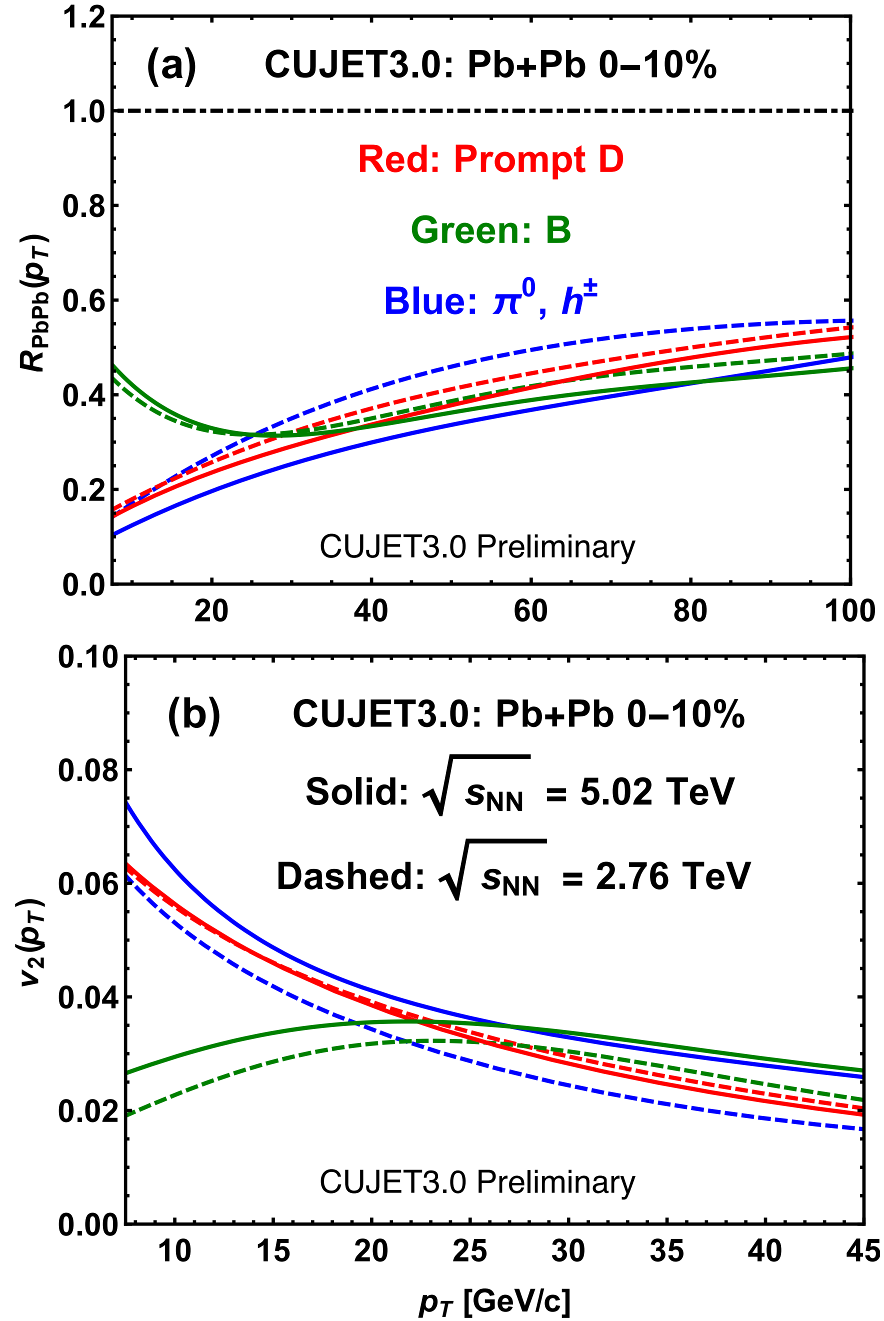

JX, Liao, Gyulassy, JHEP 2016

- The shear viscosity minimum is sensitive to how rapidly quark DOFs are deconfined
- The slope of η/s(T) is affected mainly by the temperature dependence of E and M screening masses

# CUJET3.0: D and π/h suppression ratio, Pb+Pb at 5TeV




ALICE, arXiv:1509.06888




- ❖ $R_{AA}$ and $v_2$ are approximately anti-correlated
- ❖ At a higher beam energy, D mesons are less suppressed comparing to π/h

$$dE_{rad}/dL \propto \hat{q}L \quad dE_{el}/dL \propto \hat{q}/T$$

# Summary and outlook

- For leading hadrons, it is non-trivial to quantitatively describe their high $p_T$ [$R_{AA}$ & $v_2$] + [RHIC & LHC] simultaneously.

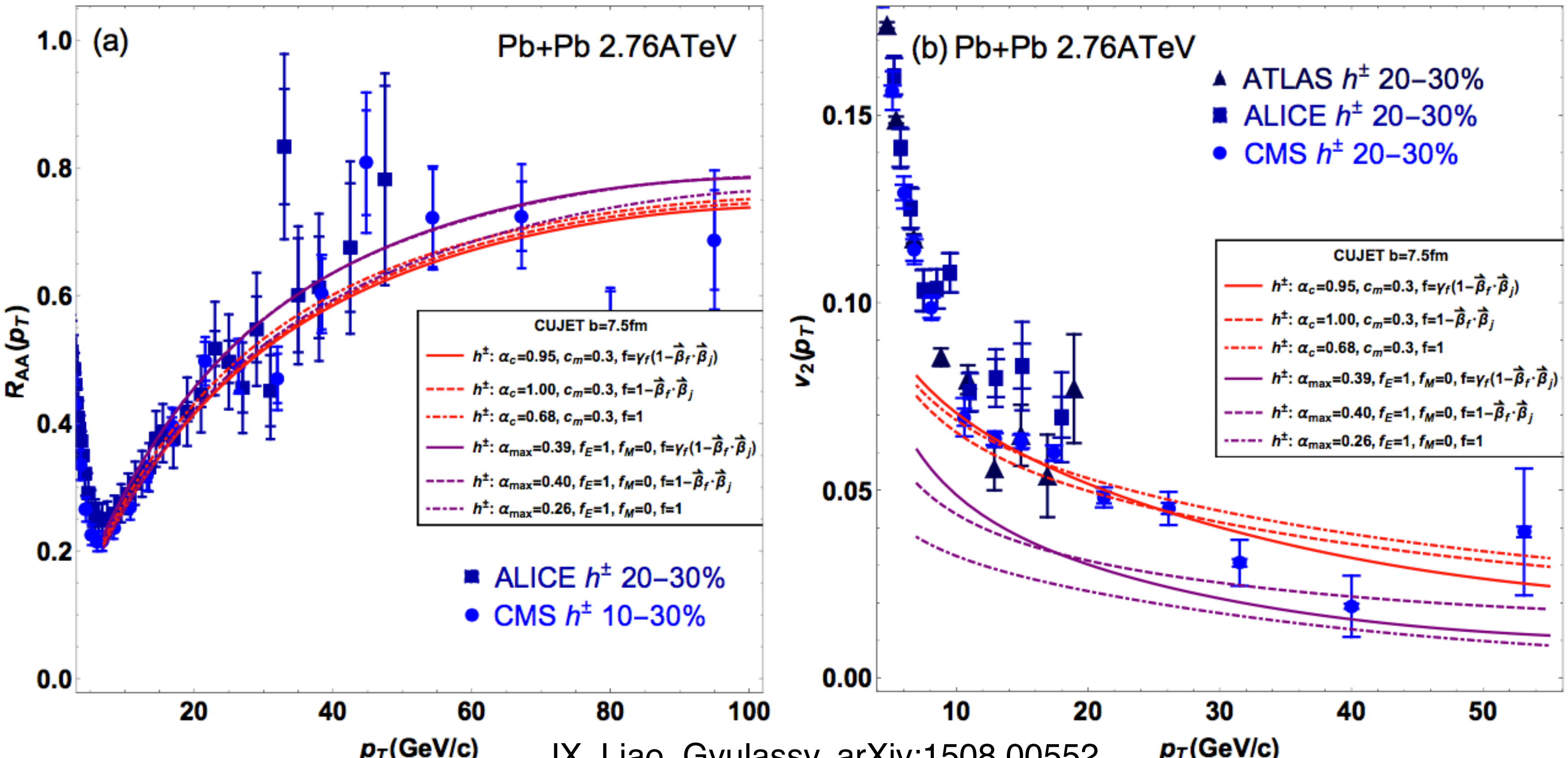
- Combining the pQCD/DGLV jet energy loss kernal and the microscopic semi-Quark-Gluon-Monopole Plasma (sQGMP) model, CUJET3.0 achieves the goal. More importantly, within CUJET3.0:
  - Long wavelength perfect fluidity is generated from short distance jet transport
  - A quantitative $\eta/s \sim T^3/\text{qhat}$ connection is established at all $T>T_c$

- The nonperturbative chromo-electric and chromo-electric structure of the sQGP near $T_c$ significantly affects the anisotropic suppression of open heavy flavors and the shear viscosity minimum

- BES@RHIC and LHC are both essential to constrain and map out the strongly non-conformal QCD confinement/deconfinement transition physics

# Relativistic corrections to jet quenching from transverse flow

$$\Gamma(\mathbf{z}) = u_f^\mu n_\mu \quad n = (1, \vec{\beta}_{jet}) \quad u_f^\mu = \gamma_f (1, \vec{\beta}_f)$$ Liu et al. 07'; Baier et al. 07'




JX, Liao, Gyulassy, arXiv:1508.00552

- Both RAA and v2 are surprisingly insensitive to the form of the relativistic flow corrections in both CUJET2.0 (pQCD+HTL) and CUJET3.0 (semi-QGP + magnetic monopoles)

# Convergence of the DGLV opacity series

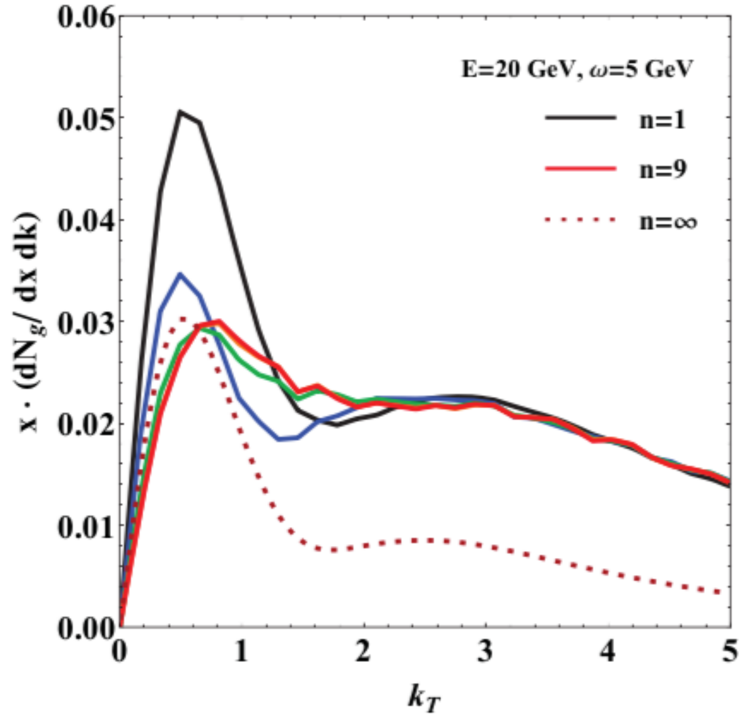
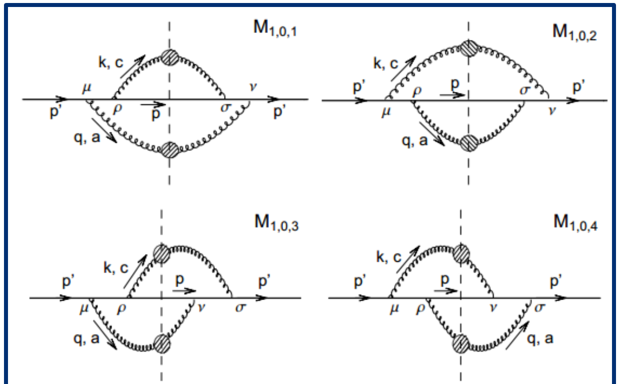



**Figure 15**. Radiated gluon transverse momentum distribution for a heavy quark jet with energy $E = 20\,\mathrm{GeV}$ traversing a brick plasma of size $L = 5\,\mathrm{fm}$ emitting a gluon with energy $\omega = 5\,\mathrm{GeV}$. The mass of the quark $M = 4.75\,\mathrm{GeV}$. The DGLV opacity series calculated up to n=1 (black), 3 (blue), 5 (green), 7 (orange), 9 (red) are shown in the figure. The opacity expansion computed up to ninth order is shown to converge to the ASW multiple soft scattering limit (maroon, dashed) for small $k_\perp \lesssim \hat{q}L \approx 1\,\mathrm{GeV}$. At large $k_\perp$, differs from the ASW limit, DGLV has a robust Laudau tail. Other parameters used in the simulation are: $\lambda = 1.16\,\mathrm{fm}$, $\mu = 0.5\,\mathrm{GeV}$, $m_g = 0.356\,\mathrm{GeV}$, $T = 0.258\,\mathrm{GeV}$, $n_f = 0$, $\alpha_s = 0.3$.

JX, Buzzatti, Gyulassy, JHEP 1408, 063 (2014)

# CUJET: to solve the heavy quark energy loss puzzle + to explain the surprising transparency of QGP at LHC

❖ Recoiling scattering centers




$$\lambda_{\rm dyn} \Longleftrightarrow \lambda_{\rm stat} = \frac{\lambda_{\rm dyn}}{c(n_f)}$$

$$\left[\frac{\mu^2}{\boldsymbol{q}^2(\boldsymbol{q}^2+\mu^2)}\right]_{\rm dyn} \Longleftrightarrow \left[\frac{\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}\right]_{\rm stat}$$

Djordjevic and Heinz, PRC (2008)

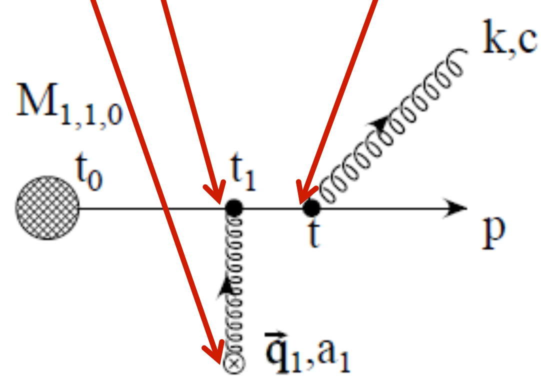
❖ Path length fluctuations: $T(\tau_{max}) = T_f$

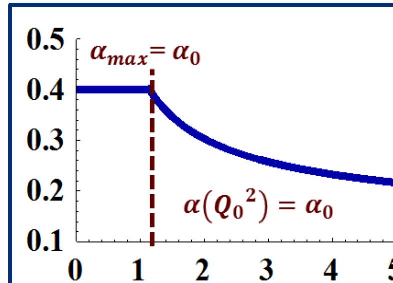
❖ Multi-scale running strong coupling

$$Q^2 = \mathbf{q}^2$$

$$Q_2^2 = q^2 - M^2 = \frac{\mathbf{k}^2}{x_+(1-x_+)} + \frac{x_+ M^2}{1-x_+} + \frac{m_g^2}{x_+}$$

$$Q^2 = (2T)^2$$




Zakharov, JETP Lett. 2008

Buzzatti, Gyulassy, 2013; JX, Buzzatti, Gyulassy, 2014

❖ Elastic: S. Peigne and A. Peshier, PRD 77, 114017 (2008)

$$\alpha_s^2 \log\frac{4ET}{\mu^2} \longrightarrow \alpha_s(\mu^2)\alpha_s(4ET)\log\frac{4ET}{\mu^2(\alpha_s(4T^2);T)}$$

# The semi-Quark-Gluon + Monopole Plasma

- Nonperturbative E sector near Tc: semi-Quark-Gluon Plasma (Pisarski, 2006; Hidaka & Pisarski 2008)
- Semi-QGP suppresses color-electric DOFs as powers of Polyakov loop

$$L(\vec{x}) \equiv \mathcal{P} \exp\left( ig \int_0^{1/T} d\tau A_0(\tau, \vec{x}) \right) \qquad (A_0^{cl})^{ab} = \delta^{ab} Q^a / g$$

$$\ell_n(Q) \equiv \langle tr L^n \rangle / N_c = \sum_{a=1}^{N_c} e^{inQ^a/T} / N_c.$$

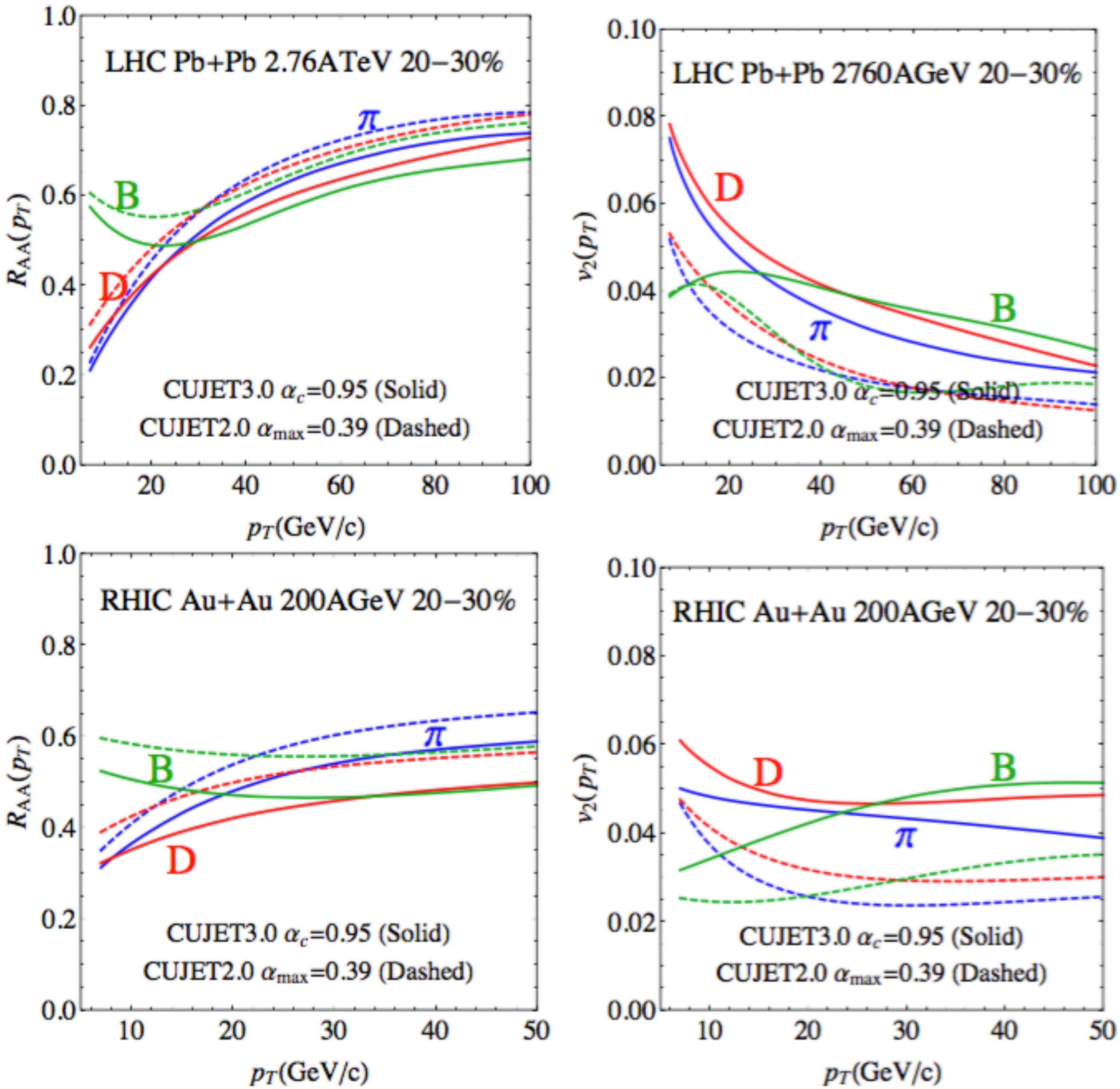
$$n_{ab}(E) = \frac{1}{e^{(E - i(Q^a - Q^b))/T} - 1} \longrightarrow \langle \sum_{ab} n_{ab} \rangle_Q \sim N_c^2 T^3 \ell^2$$

$$\widetilde{n}_a(E) = \frac{1}{e^{(E - iQ^a)/T} + 1} \longrightarrow \langle \sum_a \widetilde{n}_a \rangle_Q \sim N_c T^3 \ell$$

- semi-QGP + emergent chromo-magnetic monopoles = sQGMP

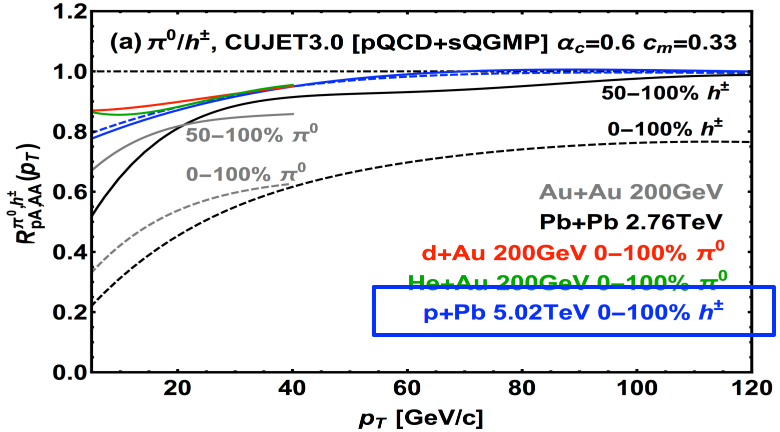
- Phenomenologically how can we implement such a microscopic sQGMP in a pQCD jet energy loss framework?

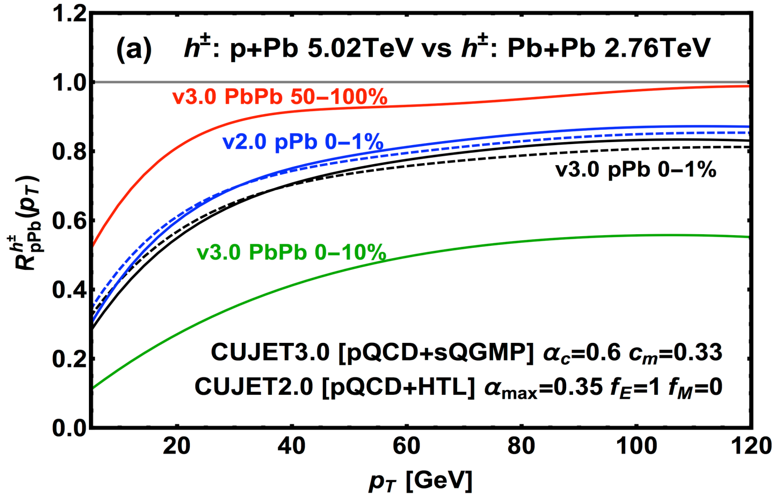
# Comparing CUJET3.0 & 2.0



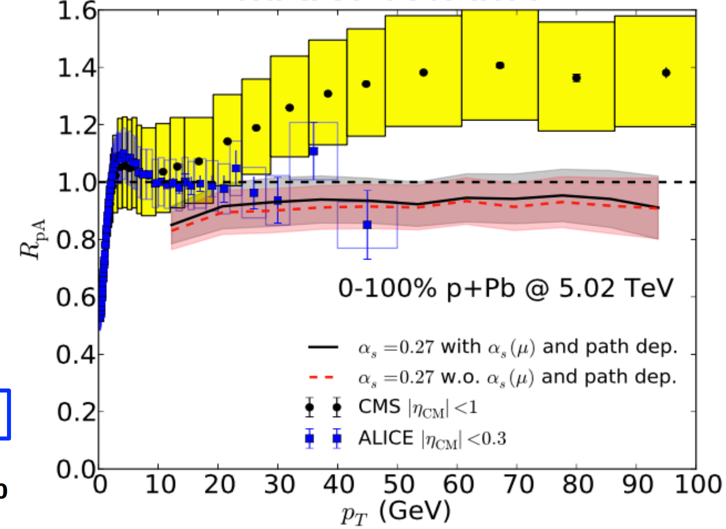
# Jet quenching in p+A?

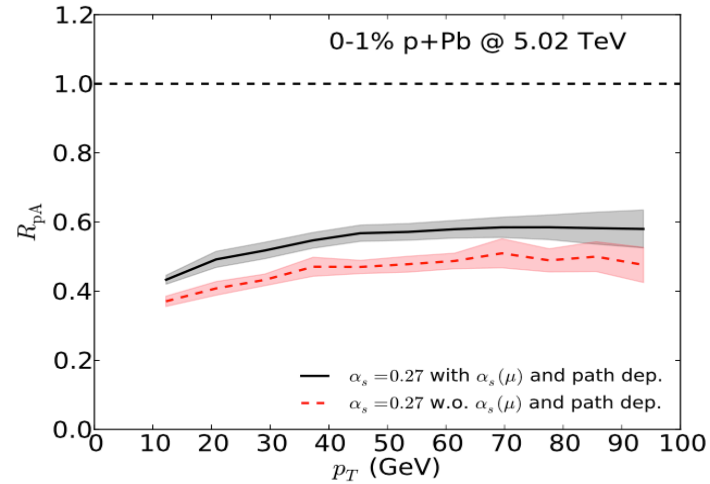
CUJET3.0/DGLV
(preliminary)




MARTINI/AMY

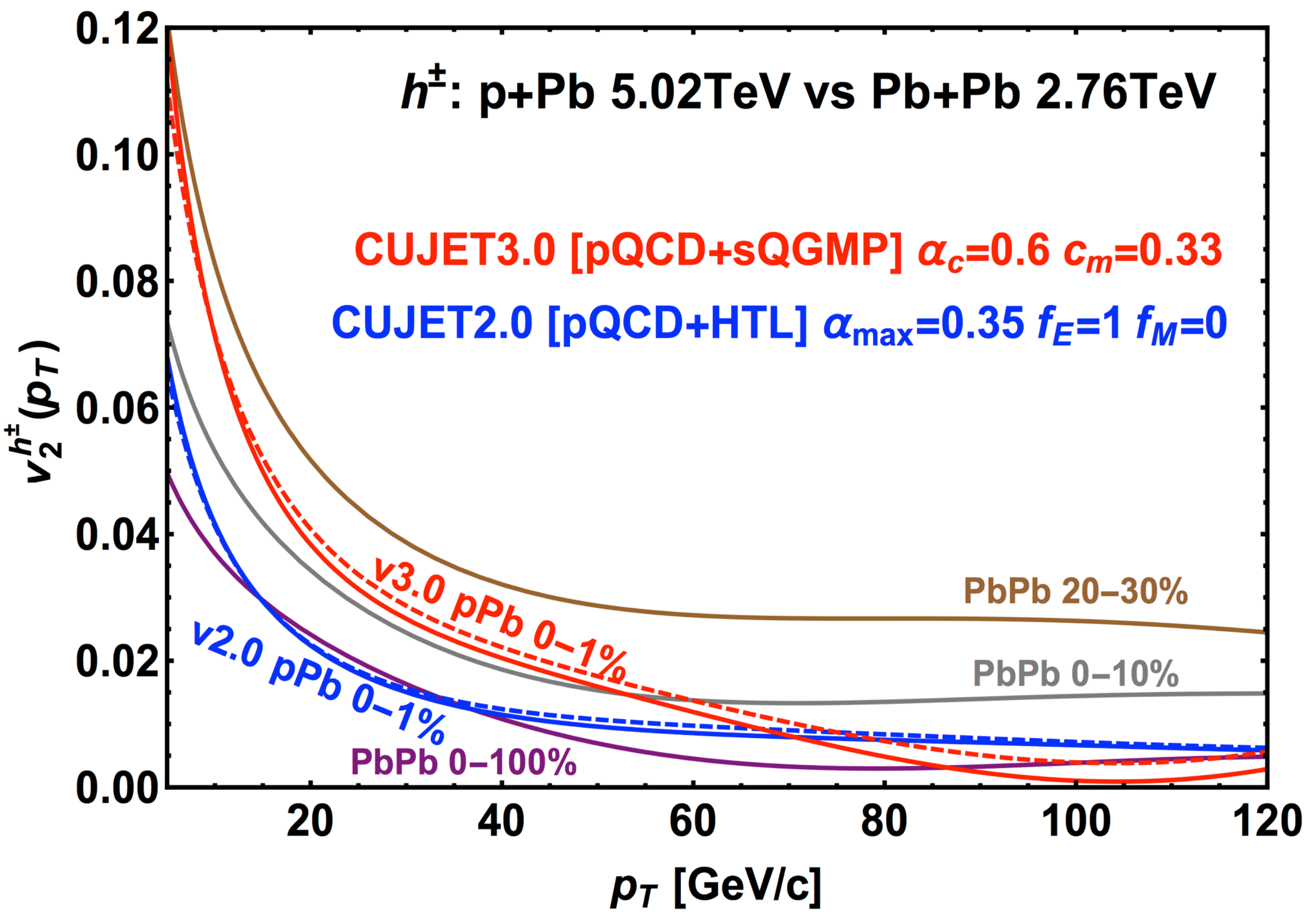


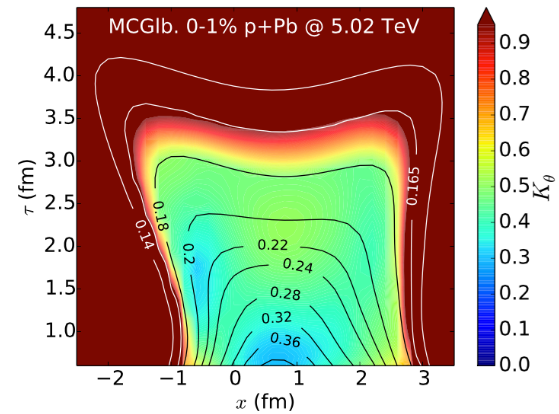




Gale, QM15

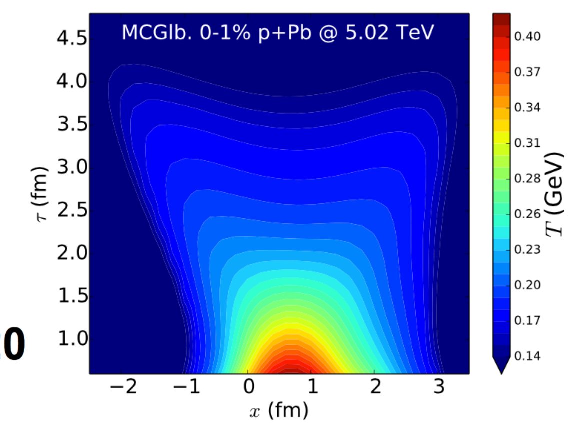
- Same pA Hydro from McGill group is used, cf. Shen et al. arXiv:1504.07989
- Central collisions see strong jet suppressions

# Azimuthal anisotropy of charged hadrons in p+A



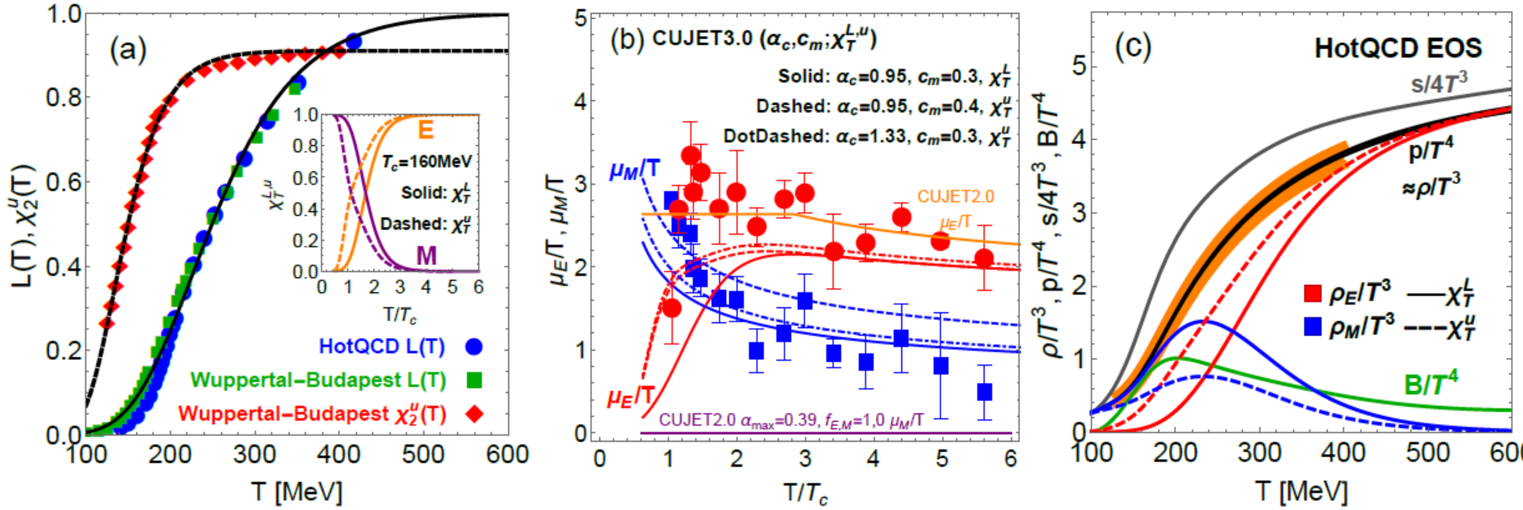

$$K_\theta \equiv \tau_\pi \theta = \frac{5\eta}{e+\mathcal{P}}(\partial \cdot u)$$

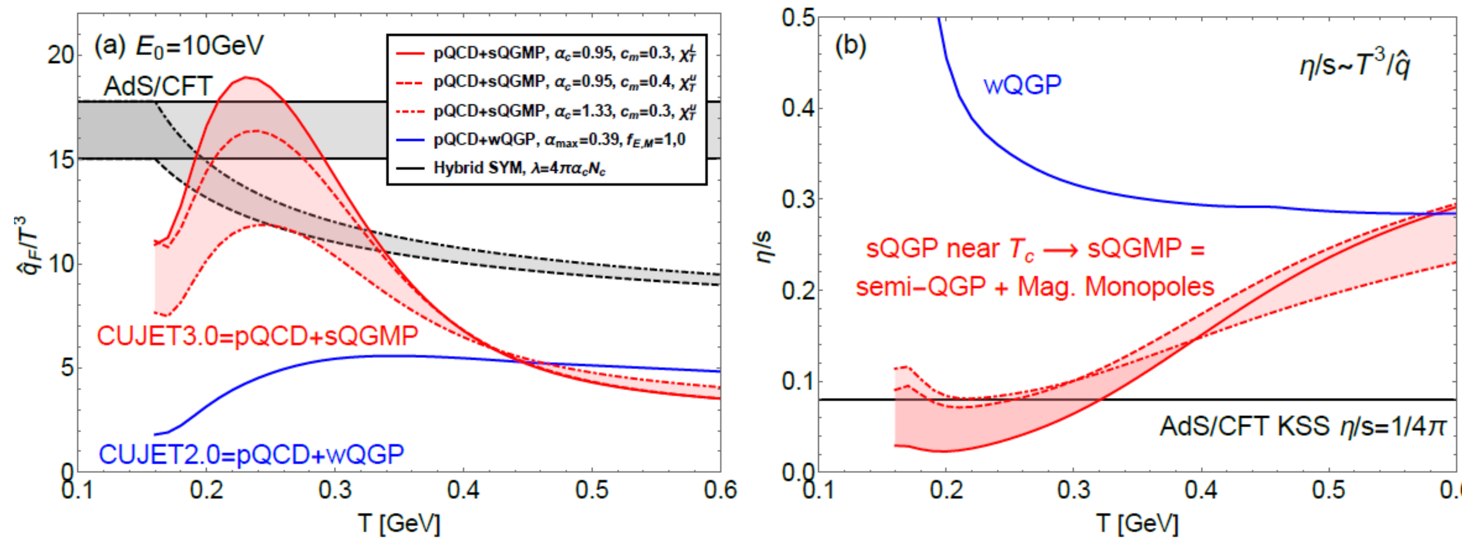



Shen et al. arXiv:1504.07989

- Significant $v_2$ up to $p_T$~30GeV in central pA collisions in CUJET (if the McGill hydro medium evolution were the correct picture)
- Compared with HTL QGP, in sQGMP, the monopoles contribute to a ~0.03 boost in high $p_T$ $v_2$, this magnitude of enhancement is similar to the one in 20-30% AA

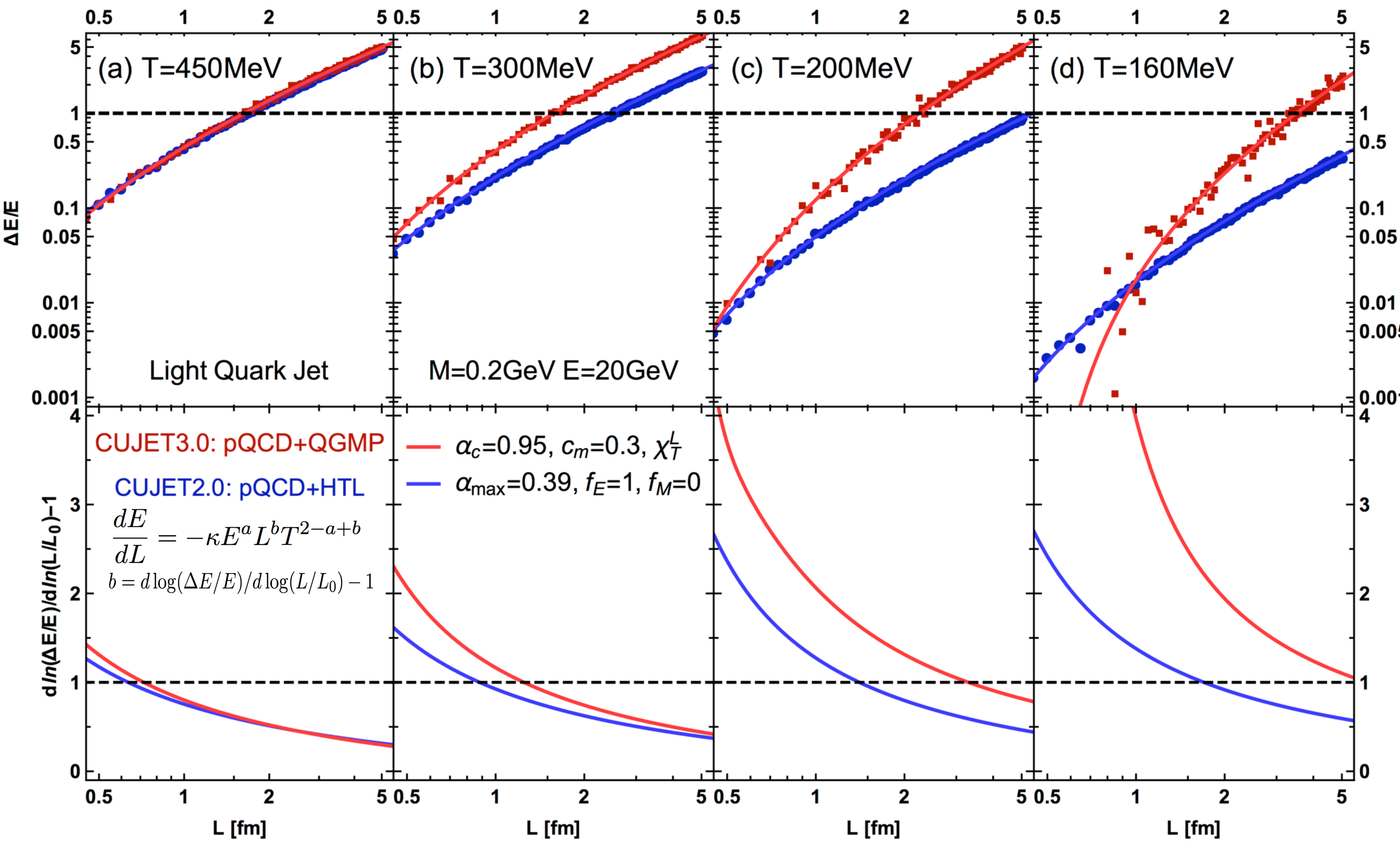
# sQGMP vs wQGP




- Long wavelength perfect fluidity from short distance jet transport

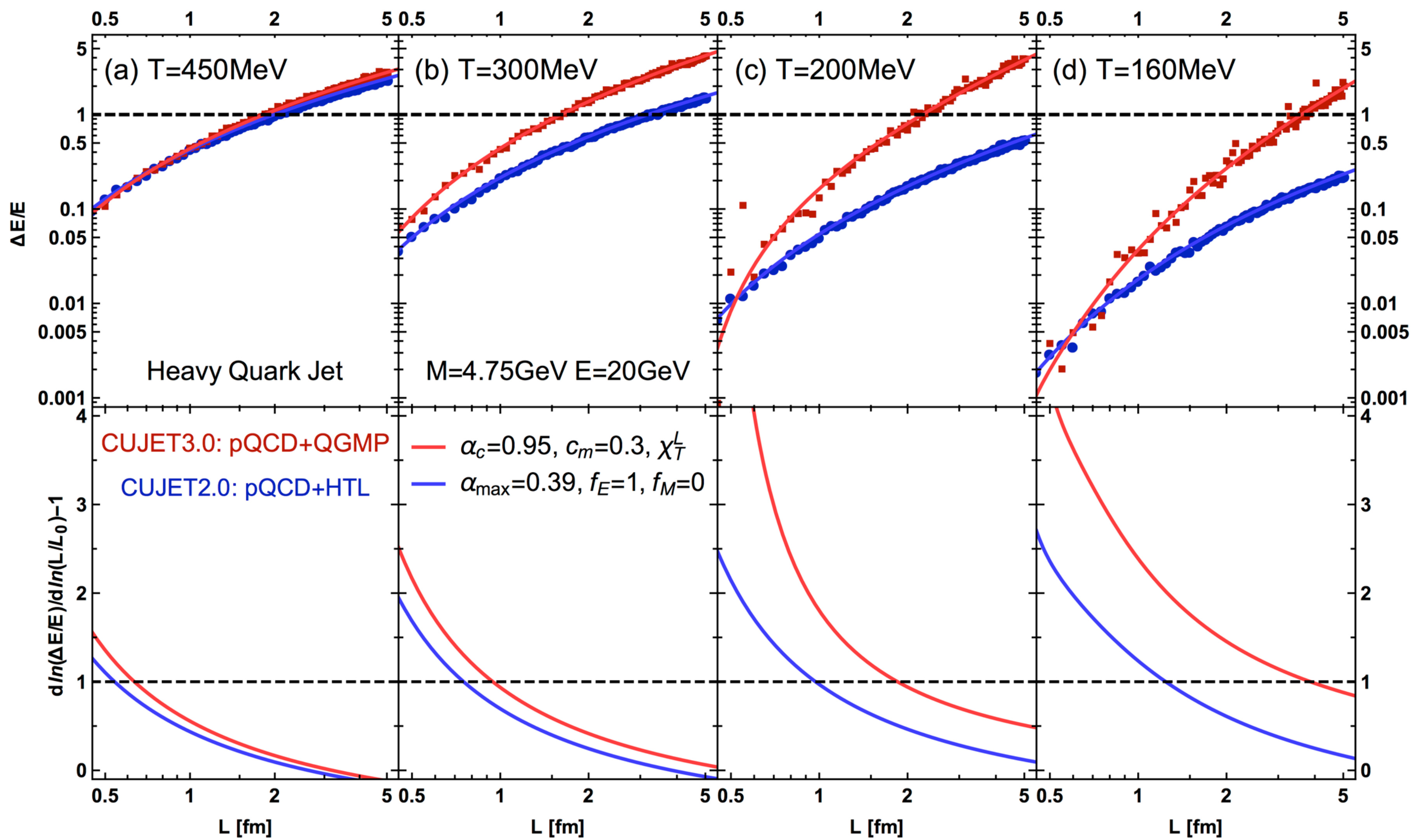
# Path length dependence of jet energy loss in sQGMP




JX, Liao, Gyulassy, JHEP 2016

❖ Monopoles bring non-perturbative effects into the pQCD energy loss theory

# Path length dependence of heavy quark energy loss in sQGMP




JX, Liao, Gyulassy, JHEP 2016